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IDENTIFICATION, DESIGN AND FINANCIAL ANALYSIS OF AN APPROPRIATE SANITATION SYSTEM FOR COASTAL AREAS OF SMALL ISLAND DEVELOPING STATES IN THE SOUTH PACIFIC

Master thesis

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submitted by:

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ABSTRACT

Rural coastal areas of Small Island Developing States in the South Pacific are often characterized by high groundwater tables, flood proneness and scarce freshwater resources. Thin and permeable soil layers featuring a limited unsaturated zone make the groundwater lens below these islands highly vulnerable to microbiological and chemical contamination. The prevalent sanitation systems (i.e. Single Pit; Dry and Pour-Flush Latrine) may cause serious degradation of groundwater quality. Hence freshwater supply on many small islands is often limited to rainwater harvesting. Flood events may cause toilets to be inoperable and pose a threat to human health by spreading faecal pathogens in the environment. The objective of this thesis is to identify, design and financially analyse an appropriate sanitation system for these rural coastal areas. The problem was approached in a literature review and during on-site research in Vanuatu. Eight sanitation systems were analysed regarding their applicability under the prevalent conditions (i.e. high groundwater table, flood proneness, limited water supply). Urine-Diverting-Dry-Toilets (UDDTs) were identified as appropriate solution. Watertight vaults built above ground make this system most suitable. Crucial design aspects of UDDTs were described and combined with findings form the on-site research. This was the basis for a technical planning of the facility. A financial analysis (comparing the prevalent Pour-Flush Latrine and the UDDT) was conducted for a potential pilot site on Emae, Vanuatu. Bills of Quantity were compiled for both systems and served as basis for the analysis. A Present Value evaluation, including the costs for construction, operation and maintenance, showed that the Pour-Flush Latrine is the preferred option from a financial perspective. Nonetheless, UDDTs are very likely to have a comparatively better Net Present Value to Pour Flush Latrines, if potential benefits and external costs are included.

KURZFASSUNG

Rurale Küstengebiete der Small Island Developing States im Südpazifik weisen oft hohe Grundwasserspiegel auf, sind bedroht von Überschwemmungen und verfügen über begrenzte Süßwasservorkommen. Aufgrund dünner Bodenschichten mit hoher Permeabilität und einer limitierten ungesättigten Zone, ist die Süßwasserlinse unter diesen Inseln äußerst anfällig für mikrobielle und chemische Verunreinigungen. Da gängige Sanitärsysteme (Single Pit; Dry und Pour-Flush Toiletten) zu einer erheblichen Verschlechterung der Grundwasserqualität führen können, sind viele Inseln auf Regenwassernutzung angewiesen. Überschwemmungen können Toiletten unbenutzbar machen, und stellen durch die Verbreitung von Krankheitserregern in der Umwelt ein Gesundheitsrisiko dar. Ziel dieser Arbeit ist die Identifikation, Planung und finanzielle Analyse eines geeigneten Sanitärsystems. Die Problemstellung wurde mittels Feldforschung in Vanuatu sowie einer Literaturrecherche bearbeitet. Acht Sanitärsysteme wurden hinsichtlich ihrer Eignung unter den vorherrschenden Bedingungen (hoher Grundwasserspiegel, Überschwemmungen, begrenzte Süßwasservorkommen) analysiert. Urine-Diverting-Dry Toiletten (UDDT) wurden aufgrund ihrer wasserdichten Bauweise als geeignete Lösung identifiziert. Wesentliche Designaspekte der UDDT wurden erläutert, mit Erkenntnissen der Feldforschung kombiniert, und weiters in der technischen Planung berücksichtigt. Mittels finanzieller Analyse für einen potenziellen Pilotstandort auf Emae, Vanuatu, wurde eine Pour-Flush Toilette mit einer UDDT verglichen. Stücklisten beider Systeme wurden angefertigt und dienten als Grundlage der Berechnung. Der errechnete Barwert zeigte unter Berücksichtigung der Bau-, Betriebs- und Wartungskosten, dass aus finanzieller Sicht die Pour-Flush Toilette zu bevorzugen ist. Jedoch ist anzunehmen, dass bei einer Nettobarwertberechung, unter Berücksichtigung aller Vorteile und externen Kosten, das UDDT gegenüber dem Pour-Flush System die bevorzugte Variante wäre.

ABBREVIATIONS

ABR	Anaerobic Baffled Reactor
ADB	Asian Development Bank
AIS	Atlantic, Indian Ocean, and South China Sea
ARGOSS	Assessing the Risk to Ground-water from On-Site Sanitation
AusAID	Australian Aid
BOD	Biological Oxygen Demand
BOQ	Bill of Quantity
CapEx	Capital Expenditure
CapManEx	Capital Maintenance Expenditure
CDM	Clean Development Mechanism
COD	Chemical Oxygen Demand
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CT	Composting Toilet
DGMWR	Department of Geology, Mines and Water Resources
EAWAG	Swiss Federal Institute of Aquatic Science and Technology
EcoSanRes	Ecological Sanitation Research
ENSO	El Niño-Southern Oscillation
GIZ	German development agency
HDPE	High-Density Polyethylene
IRC	International Water and Sanitation Centre
JMP	Joint Monitoring Programme for Water Supply and Sanitation by WHO and UNICEF
MDGs	Millennium Development Goals
MOH	Ministry of Health
NGO	Non-Governmental Organization
NPV	Net Present Value
OpEx	Operational Expenditure
O&M	Operation and Maintenance
PE	Polyethylene
PP	Polypropylene
PVC	Polyvinyl Chloride
SDG	Sustainable Development Goals
SIDS	Small Island Developing States
SOPAC	South Pacific Applied Geoscience Commission
SSWM	Sustainable Sanitation and Water Management Toolbox
TC	Tropical Cyclone
VIP	Ventilated Improved Pit
UASB	Upflow Anaerobic Sludge Blanket
UDDT	Urine-Diverting-Dry Toilet
UDFT	Urine-Diverting Flush Toilet
UD	Urine Diversion
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations International Children’s Emergency Fund
uPVC	unplasticized PVC
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNEP	United Nations Environment Programme
UV	Ultraviolet
VMGD	Vanuatu Meteorology and Geo-hazards Department
VMOH	Vanuatu Ministry of Health
VNSO	Vanuatu National Statistics Office
VPMU	Vanuatu Project Management Unit
Vt	Vatu, currency in Vanuatu
WASH	Water, Sanitation and Hygiene
WECF	Women Engage for a Common Future
WHO	World Health Organization
WSP	Water and Sanitation Program

1. INTRODUCTION

Small island developing states (SIDS) are a group of 58 developing countries and least developed countries, that spread over the following three geographical regions: the Caribbean, the Pacific and the Atlantic, Indian Ocean, and South China Sea (AIS) (UN, 2019). These islands are confronted with specific challenges in the water, sanitation and hygiene sector. Their water resources are extremely fragile *'[…] due to their small size, lack of natural storage, competing land use, and vulnerability to natural and anthropogenic hazards, including drought, cyclones, and urban pollution'* (Dahan, 2018, p. 7).

Many small islands have no surface water bodies and depend on rainwater collection or limited groundwater resources. On small coral or limestone islands the groundwater forms a thin freshwater lens (maximum of 10 – 20 m thickness), which underlies the whole island and floats above the denser seawater. Consequently, the groundwater table on low-lying islands is often very shallow (Falkland, 2002). It can only be tapped at shallow depths, to avoid drawing in saline water (Dillon, 1997). Further the soil type and infiltration rate play an important role in the hydrological cycle. Typically, coral or small limestone islands and sandy coastal areas feature a thin and highly permeable soil layer (Falkland, 2002). Since soils on these islands are generally coarse textured, the infiltration rates are high and the potential to filter or adsorb organisms is low (Dillon, 1997). The unsaturated zone in the soil is important for attenuation of microbiological and chemical contaminants, since die-off rates are significantly higher than in the groundwater (i.e. saturated zone). Especially the upper soil layers are most effective, as the biological activity is greatest in these areas (ARGOSS, 2001). Since the thickness of the unsaturated zone is limited on low-lying islands, the migration of pollutants to the groundwater is facilitated. All these conditions render the groundwater resources highly vulnerable to contamination (Dillon, 1997).

Hence inappropriate sanitation systems, discharging untreated or partially treated wastewater, often result in a serious degradation of the water quality. This problem is most significant in areas with high population densities, like urban centres or peri-urban settlements. However, high bacterial levels in the groundwater are also a major problem of many smaller villages. The prevalent pit-based sanitation systems often result in a direct contamination, as it is common practice in the Pacific to dig pits to the water table (Falkland, 2002). Where inadequate sanitation facilities pose a risk of pollution, it can result in severe adverse impacts on the health of local communities relying on groundwater supply (Dillon, 1997). Hence collected rainwater is often the only safe source of drinking water. Especially in rural areas rainwater harvesting is often the most important drinking water supply source (VNSO, 2014).

The exposure of SIDS makes them particularly vulnerable to natural disasters like cyclones, earthquakes, floods and droughts (Falkland, 2002). The occurrence of some of these disastrous events is affected by climate change. *'Increasingly variable rainfall, cyclones / hurricanes, accelerating storm water runoff, floods, droughts, decreasing water quality and increasing demand for water are so significant in many small island countries that they threaten the economic development and the health of their people'* (Overmars & Gottlieb, 2009, p.2). Obviously extended drought periods have a huge influence on islands relying on rainwater collection. These often have to be supplied with water imports by boats or barges (Falkland 2002). Increasing frequency of floods and cyclones threatens sanitation infrastructure, which is likely to exacerbate the spread of communicable and vector-borne diseases (PSIDS, 2009). Floods can cause toilets to overflow, resulting in a spread of faecal pathogens in the environment (Stenström et al, 2011).

These issues show, that on small islands sustainable sanitation solutions are crucial to protect human health, natural resources and the environment. *'There is an urgent need for greater use of technologies such as water less toilets in small islands to assist in the process of managing water demand and reducing the degradation of water quality'* (Falkland, 2002, p. 40).

2. OBJECTIVE AND STRUCTURE OF THESIS

The general objective of this thesis is to identify, design and financially analyse an appropriate sanitation system for rural, coastal areas of low-lying, small island developing states, featuring high groundwater tables, flood proneness and limited water supply. The thesis focuses on Vanuatu, as representative example for the prevalent conditions.

At the beginning some background information about Vanuatu is provided in chapter 3 (this section was written in cooperation with Dominik Raab (Raab, 2017). This part of the thesis also refers to and reviews the foregoing environmental conditions and also current constraints for sanitation systems there. Subsequently fundamentals of cost analysis in the sanitation sector are described (chapter 4), followed by the methods used in the course of this thesis (chapter 5).

Basically, the thesis is divided into three main sections:

I. SANITATION SYSTEM analysis (chapter 6)

This chapter analyses the following eight systems:

- Single Pit System,
- Waterless Pit System without Sludge Production,
- Pour-Flush Pit System without Sludge Production,
- Waterless System with Urine Diversion,
- Biogas System,
- Blackwater Treatment System with Infiltration,
- Blackwater Treatment System with Effluent Transport and
- Blackwater Transport to (Semi-) Centralized Treatment System / optional UDFT

in regard of the applicability under the aforementioned conditions. Based on several criteria, one system is selected for subsequent planning steps.

II. DESIGN ASPECTS OF THE URINE-DIVERTING-DRY-TOILET SYSTEM (chapter 7)

The second main chapter focuses on detailed, technical design recommendations for the selected sanitation system. Although the chosen system is a comparatively straight-forward on-site sanitation technology, a wide range of structural details must be considered in order to guarantee a functioning system.

Chapter 8 provides the technical planning and material requirements for the construction of two sanitation options at a potential pilot site on Emae, Vanuatu. The first system, the Urine-Diverting-Dry-Toilet (UDDT), was chosen as result of the preceding sanitation system analysis. The second system is the commonly used Single Pit technology (i.e. Pour-Flush Latrine).

III. FINANCIAL ANALYSIS OF UDDT AND POUR-FLUSH LATRINE ON EMAE, VANUATU (chapter 9)

The final section presents a financial analysis. More specifically, it features a financial comparison (Present Value evalution) between the two sanitation options (i.e. UDDT and Pour-Flush Latrine). The costs of each system are calculated for a specific pilot site on Emae, Vanuatu.

Finally, chapter 10 contains the conclusion and discussion of the thesis.

3. VANUATU BACKGROUND INFORMATION

The following chapter was written in cooperation with Dominik Raab (Raab, 2017).

Vanuatu is an island state located in the South Pacific Ocean, Oceania. About 234.000 inhabitants (i.e. ‘ni-Vanuatu’ or ‘ni-Van’) populate 63 of the 83 main islands (census 2009). The official languages are English, French and Bislama (Pidgin English used in Vanuatu), but more than 105 local languages are spoken throughout the archipelago (VNSO, 2011a; SOPAC, 2007; VNSO, 2002). ‘*Vanuatu is an agriculture-based largely subsistence economy*’ (SOPAC, 2007, p. vi). Subsistence farming plays an important role especially in rural areas where 39% of the population are subsistence workers (VNSO, 2011a).

3.1 GEOGRAPHY AND GEOLOGY

Vanuatu consists of 83 main islands (total land area 12.281km²) extending 1176km from north to south in a Y-shape (Figure 1). The islands are spread over an area of 612.000 km² and are divided in six provinces (Torba, Sanma, Penama, Malampa, Shefa, and Tafea). Only 12 islands are significant regarding economy and population, the capital Port Vila is located on the most populous island Efate (Shefa Province), the second urban area named Luganville is on the biggest island, Espiritu Santo (Sanma Province). Suva (Fiji) is about 1071km east, Honiara (Solomon Islands) 1288km south-west and Cairns (Australia) 2394km west of Port Vila (VNSO, 2011a; VNSO, 2002).
Many islands are mountainous since they are the summits of mountain ranges rising from the ocean, with 35% of the total area lying 300m above sea level and 55% featuring slopes > 20°. The highest peak is called Mount Tabwemasana (Espiritu Santo) with 1879m, Ambae, Ambrym and Tanna have peaks over 1000m as well. About ¾ of the country is covered with natural vegetation, forests and secondary growth are mainly found on steeper terrain. Plains are characterized by coconut plantations and agriculture (VNSO, 2002).
The geographic situation of island states in the pacific, in particular the *‘[r]emoteness, in conjunction with small size and internal dispersion, imposes additional costs of trade and transportation […]. The same factors also push up the cost and complexity of providing public services and fulfilling the basic functions of government’* (Esler, 2015, p. 2).

Vanuatu is part of the Pacific Ring of Fire and lies at the edge of the Pacific tectonic plate. The plate is forced up by and over the Indo-Australian plate which is the reason for frequent earthquakes and volcanic activity (VNSO, 2002).
Nine active volcanoes are still continuously creating new land. Two of these active volcanoes are submerged in the sea and 7 are found on various islands, with Mount Yasur (Tanna) being the most famous and accessible volcano, and Mount Garet (Gaua) being possibly the most dangerous one (SOPAC, 2007; VNSO, 2002).
Vanuatu is young from a geologically perspective, as the northern islands (Espiritu Santo, Malekula and Torres islands) emerged some 22 million years ago when a series of earth movements, i.e. geological activity of the New-Hebrides subduction zone, caused huge submerged mountains to be surfaced. The southern islands (Maewo and Pentecost) arose between 5 and 11 million years ago. The remaining islands have been formed less than 5 million years ago. Only a fraction of the present land was above sea level about two million years ago, a slow and continues uplift caused today's shape of the terrain and formed fringing coral reefs (VNSO, 2002). This uplift is still present, with *‘[…] some areas of Vanuatu such as west Efate are being uplifted at 2 cm per year whilst other areas are subsiding’* (SOPAC, 2007, p. 14).
Falkland (2002, p. 3) describes Vanuatu’s island geology to be *‘[…] predominantly volcanic with coastal sands and limestone’*. According to Nunn et al. (2016), almost 60% of Vanuatu’s islands are of volcanic origin, approximately 17% of limestone and of composite origin, respectively, the remaining islands are elevated coral reefs.

3.2 MAP

Figure 1: Map of Vanuatu with its six provinces Torba, Sanma, Penam, Malampa, Shefa, and Tafea (Gaba, 2013, adapted).

3.3 POPULATION

The last census from 2009 determines a total population of 234.023 and a growth rate of 2.3% from 1999 – 2009 (Table 1). The two urban areas Port Vila (44.039 inhabitants) and Luganville (13.156 residents) account for 24.4% of the total population. The average household size is 4.8, more than 10% of the households have 10 members or more. The median age is 20.5 years, 39% of the population is younger than 15 years and only 6% are older than 60 years. Approximately 30% of people above the age of 15 have a regular income. About 39% of the rural population's main activity is subsistence work (i.e. growing and/or gathering produce, or fishing) which accounts for 60% of the main income in rural areas (VNSO, 2011a).

Table 1: Population size, growth rate, population density and doubling time from 1989, 1999 and 2009, '89 – '99, '99 - '09, respectively (VNSO, 2011a, p. 4, 7, adapted).

Region	**Total population size**			**Growth rate/a** [%]		**Population density** [people/km²]		**Doubling time** [a]	
	1989	**1999**	**2009**	**'89 – '99**	**'99 – '09**	**1999**	**2009**	**1999**	**2009**
Vanuatu	142.419	186.678	234.023	2.6	2.3	15	19	27	31
Urban	25.870	40.094	57.195	4.2	3.5	NA	NA	17	20
Rural	116.549	146.584	176.828	2.2	1.9	NA	NA	32	37
Torba	5.985	7.757	9.359	2.5	1.9	9	11	28	37
Sanma[a]	25.542	36.084	45.855	3.3	2.4	8	11	21	29
Penama	22.281	26.646	30.819	1.7	1.5	22	26	41	48
Malampa	28.174	32.705	36.727	1.4	1.2	12	13	49	60
Shefa[a]	38.023	54.439	78.723	3.4	3.7	36	52	20	19
Tafea	22.414	29.047	32.540	2.5	1.1	18	20	28	62

[a] Shefa and Sanma include the urban areas of Port Vila and Luganville

The focus of this thesis lies on rural areas, where more than ¾ of Vanuatu's population live (VNSO, 2011a). The rural population is *'generally found in coastal villages or near provincial centres'* (AusAID 2006a, p. 4).

About 75% of the total population and 66% of the rural population live within 1 km distance from the coast. Figure 2 shows the distribution of rural village sizes (households per village) situated within 1km distance from the coast (red) and the corresponding inhabitants (orange) (note: adjacent suburbs of the two urban areas are excepted). More than 42% of the 1151 rural coastal villages consist of up to ten households, corresponding to ~15% of coastal inhabitants. Over 80% of rural coastal villages have 30 or less households, accounting for ~55% of the residents. The average rural household size is 4.91 people (VNSO, 2014, pers.comm., 28 October).

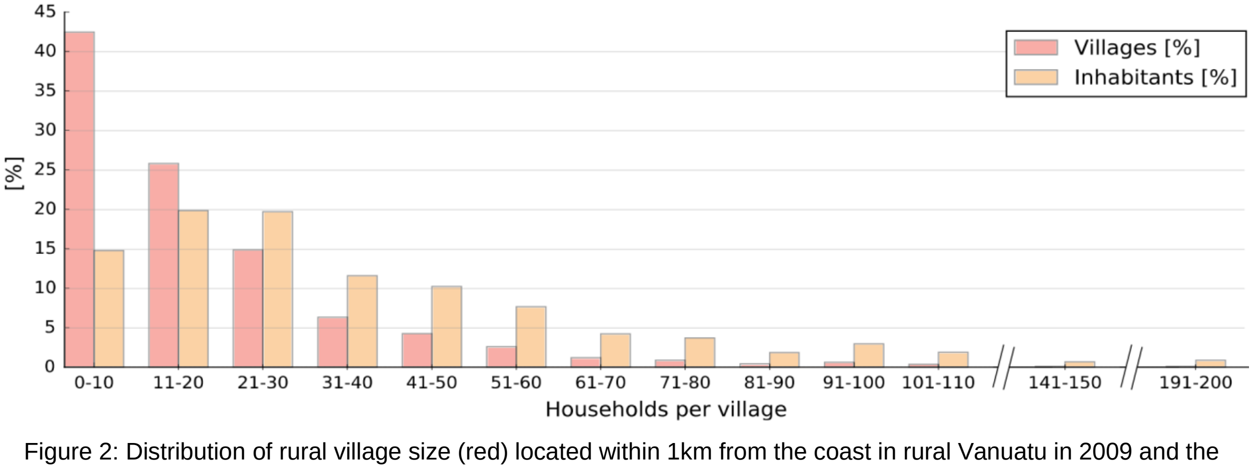

Figure 2: Distribution of rural village size (red) located within 1km from the coast in rural Vanuatu in 2009 and the corresponding share of inhabitants (orange) (Port Vila, Luganville and adjacent suburbs excluded in this chart) (based on VNSO 2014, pers.comm.,

3.4 CLIMATE, NATURAL DISASTERS AND GLOBAL WARMING

Vanuatu's climate differs greatly within its north and south extent and is substantially influenced by the South Pacific Convergence Zone. The average temperatures range between 23.5 and 27.5°C, depending on the geographical location (Australian Bureau of Meteorology & CSIRO, 2011a). The north is tropical, humid and quite wet with an average annual rainfall of up to 4587mm in Sola, the south is less wet with the lowest rainfall of 1288mm/a in Whitegrass (VMGD, 2014, pers.comm., 3 February; Sullivan & Guglielmi, 2007). The decennial average rainfall per year (2004 – 2014) for six gauging stations spread over Vanuatu is shown in Figure 3. Rainfall patterns of bigger islands are influenced by mountains, resulting in higher precipitation on windward sides and lower rainfall on leeward side, especially in the dry season. Vanuatu's climate is further influenced by the El Niño-Southern Oscillation (ENSO). This phenomenon influences the climate of the whole world and appears in Vanuatu in form of El Niño (rainy season delayed and drier, dry season cooler), La Niña (rainy season earlier and more wet, dry season warmer) or a neutral phase. The wet and warmer season is from November to April, the dry and colder one from May to October (Australian Bureau of Meteorology & CSIRO, 2011a).

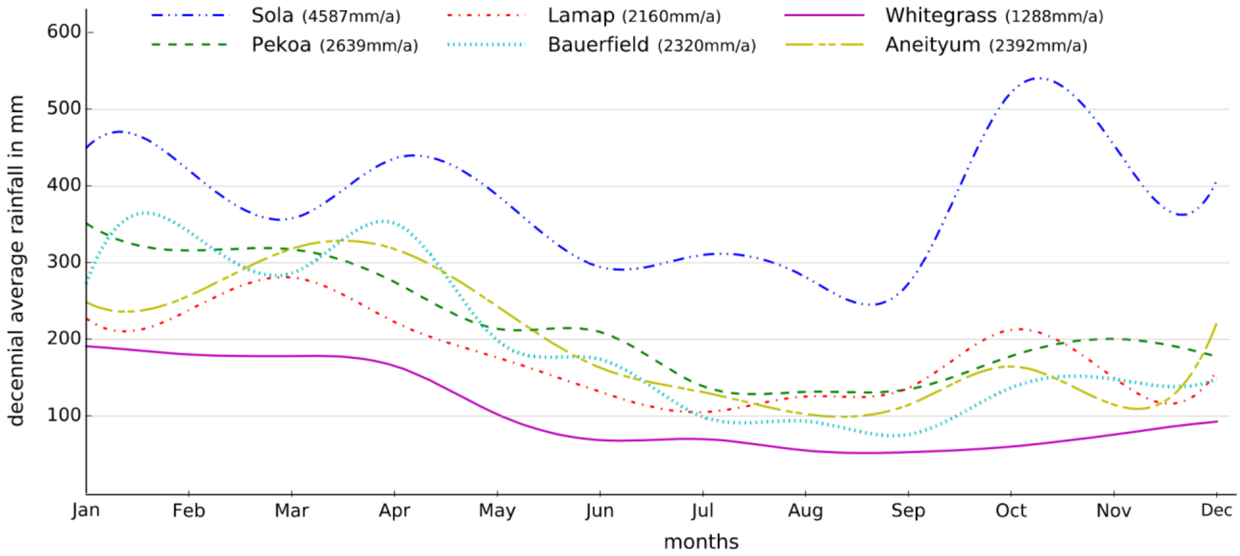

Figure 3: Decennial average monthly rainfall from six gauging stations spread over Vanuatu (2004 – 2014; for locations see *Figure 1*) (based on VMGD, 2014, pers.comm., 3. February 2015).

'Vanuatu is situated on the Ring of Fire making it prone to numerous and severe earthquakes, and is in the centre of the South Pacific's Cyclone Alley' (SOPAC, 2007, p. ii). It is further vulnerable to natural disasters like floods, landslides, volcanic eruptions, tsunamis, droughts and storm surges (Bani, 2010). The World Risk Report ranked Vanuatu's risk to be harmed by an extreme natural event as number one by far for the sixth time in a row since it was first published in 2011 (Mucke et al., 2016).

FLOODS

Low-lying coastal regions and low-lying atolls are prone to flooding and in further consequence erosion, caused by storms, intense rainfall and/or sea level rise (SOPAC, 2007). Floods also occur inland on low-lying flood plains of rivers and are either caused by sustained rainfall during the wet season, intense rainfall in La Niña years, or cyclones (UNESCO, 2012).

CYCLONES

Two to three cyclones pass Vanuatu per year during the wet season on average (most frequent in January and February), but there is a high interannual variability (Australian Bureau of Meteorology & CSIRO, 2011a). In March 2015, one of the strongest cyclones ever recorded in the region, Tropical Cyclone (TC) 'Pam' (category 5), hit Vanuatu with wind speeds of 250km/h and wind gusts up to 320km/h. The cyclone caused 11 fatalities, ~65.000 people were displaced from their homes and ~16.000 dwellings were damaged or destroyed. The livelihood of more than

80% of the rural population has been compromised due to extensive crop losses. Over 70% of the sanitation infrastructure has been destroyed in the four affected provinces, since the most common systems, pit toilets and VIPs, are mainly out of local bush materials. Regarding water supply, major damage was done to rainwater catchment structures through strong winds, flying debris and fallen trees (Esler, 2015).

DROUGHTS

Parts of the country are subject to severe droughts periodically. Moderate droughts occur once to twice, and severe droughts approximately once within 20 years (Australian Bureau of Meteorology & CSIRO, 2011b; Bani, 2010). West Ambae, Ambrym, Epi and Torba are often affected by droughts during the dry season (SOPAC, 2007).

GLOBAL WARMING

The impacts of global warming are expected to be manifold, the most important in the context of this thesis are less frequent, but more intense cyclones, more extreme rainfall days, and rising sea levels. Furthermore, there will be more very hot days, change in rainfall patterns (decrease of dry seasons and increase of wet seasons rainfall) and increase of the ocean's acidity (Australian Bureau of Meteorology & CSIRO, 2011a). Relative sea level records determine a sea level rise of +2.2mm/a, satellite-based measurements estimate it at +6mm/a (Australian Bureau of Meteorology & CSIRO, 2011b; AusAID, 2006b). Table 2 shows identified climate-sensitive health risks that are likely to arise in Vanuatu in the future.

Table 2: Climate-sensitive health risks that may arise from climate change in Vanuatu (Spickett et al., 2013, p. 48).

Risk category	Health issue
Extreme	Water-borne diseases, Food-borne diseases
High	Vector-borne diseases, Malnutrition, Non-communicable diseases, Temperature-related illnesses, Occupation-related illnesses
Medium	Respiratory infections, Skin conditions, Eye diseases, Mental health disorders, Traumatic injuries and deaths

3.5 WATER SUPPLY

'*Water supply does not meet demand in either urban or rural areas*' (SOPAC, 2007, p. iv). Vanuatu's larger islands are endowed with groundwater resources and mostly surface water, some smaller islands lack both potential sources of water (e.g. Mataso and Buninga from Shepherd Islands, all islands from the Torres Group, small islands off Malekula and Santo). Information regarding groundwater or surface water quality is hardly available. Outdated data from the aquifers supplying the two urban centres attesting them good quality, but some isolated locations have had elevated levels of nitrogen and/or faecal coliform bacteria. Surface water quality is believed to be deteriorated in many places, but data is lacking (SOPAC, 2007).

The water supply of the two urban centres are fed by shallow groundwater aquifers via open wells and bores, costs are covered via fees and tariffs. A French operating, private company (UNELCO) is responsible for the water supply in Port Vila until 2032, Public Works provide service in Luganville, and in the provincial centres Isangel and Lakatoro (Government of Vanuatu, 2010; SOPAC, 2007). Increasing pressure on aquifers due to the high and continuous population growth in agglomeration areas cause decreasing water levels (Sullivan & Guglielmi, 2007).

Rural areas draw on different sources such as springs, wells, surface water and rainwater collection which is usually stored in ferrocement or polyethylene (PE) tanks. Rivers are fluctuating seasonally and are often contaminated from upstream pollutants (human and/or animal origin). The quality of the supplied water is often low, supply systems in rural areas are partly in poor condition or even not existent (AusAID, 2006a). A report by SOPAC (2007) highlights that a quarter of rural water supply systems need major repairing, another quarter minor repairs. '*Many water sources are unprotected and affected by pollution, and in some cases contaminated by* *volcanic ash and gas emissions, and increasingly, saline intrusion to groundwater*' (SOPAC, 2007, p. iii). Table 3 shows the source of drinking water of rural and urban households compiled in 2013. 90.4% of households (rural: 87.5%, urban: 97.2) obtain water from improved sources. Piped water availability differs substantially between rural (30%) and urban areas (64%), but 85% of the households have water on their premises (urban: 97.4, rural: 79.8%). The proportion of 37.3% of rural households relying on rainwater is remarkable (VNSO, 2014).

The ratio of rural households which have to travel to the next water source improved from ~60% (2007), to 40% (2010) and finally 15% (2013) (VNSO, 2014; VNSO, 2012, VMOH, 2008).
An analysis by Cleary (2011, as cited in ISF-UTS, 2011) denotes past data up to 2008 to be '*unrepresentative* [… due to] *varying interpretations of 'improved' supply used by surveyors*' (ISF-UTS, 2011, p. 1). A review has shown a decrease of rural improved water supply coverage in the period 1999 – 2006 from 69 to 65%. UNELCO estimates urban water supply coverage at only ~80% (ISF-UTS, 2011; Government of Vanuatu, 2010; SOPAC, 2007).

Table 3: Source of drinking water of rural and urban households in Vanuatu (VNSO, 2014, p. 21, adapted).

Source of drinking water	**Households [%]**		
	Rural	**Urban**	**Total**
Improved source (subtotal)	(87.5)	(97.2)	(90.4)
Piped water into dwelling/yard	30.2	63.6	40.2
Public tap/standpipe	7.2	4.4	6.4
Tube well or borehole	1.9	0.2	1.4
Protected dug well	7.3	2.8	5.9
Protected spring	3.5	0.5	2.6
Rainwater	37.3	25.8	33.9
Non-improved source (subtotal)	(9.5)	(2.5)	(7.4)
Unprotected dug well	2.3	0.3	1.7
Unprotected spring	6.8	0.0	4.8
Tanker truck	0.3	0.3	0.3
Bottled water	0.1	1.9	0.6
Other	2.9	0.3	2.1
Total	100.0	100.0	100.0

3.6 Sanitation

There is no specific legislation nor any ministry or department in charge of sanitation in Vanuatu. The 'National Water Strategy for Vanuatu (NWS) 2008 – 2018' suggested to establish a 'Department of Water (DoW)' which would be responsible for sanitation, but the strategy has not been approved by the government so far. The 'Department of Geology, Mines & Water Resources' and the 'Ministry of Health' are both implementing scattered sanitation projects, but there is no overall coordination or a master plan due to the lack of leadership (ISF-UTS, 2011).

In general, there are no sewer systems in Vanuatu, except for a very limited network in the capital Port Vila (Government of Vanuatu, 2010). The hospital and three hotels in Port Vila are equipped treatment facilities, but these are not well maintained (Castalia, 2005). A centralized system for Port Vila is planned, but a final decision which treatment will be used is pending (Kassis, 2010).
Rural areas '*have very poor sanitation facilities mostly comprising pit latrines or bush toilets*' (SOPAC, 2007, p. iii). Flush toilets are not widely used in rural areas '*because there is no piped water system to provide the water required for a flush toilet system*' (VNSO, 2013, p. 70).

'*In the small islands* [of Vanuatu,] *the water table is elevated and the underground water is very susceptible to contamination from latrines*' (Kingston, 2004, p. 2). Water supplies are often polluted due to wastewater runoff caused by heavy rainfall or floods, surface water contaminated by human and animal waste, and/or the lack of a proper source protection (Kingston, 2004). Especially higher population densities near urban areas cause inland ground- and surface waters to be contaminated and coastal water quality to be diminished (SOPAC, 2007).

'*Households without proper toilet facilities are more exposed to the risk of diseases such as dysentery, diarrhoea and typhoid fever than those with improved sanitation facilities*' (VNSO, 2014, p. 22). Diarrhoea and worm infestation due to improper sanitation and water supply is of major concern in Vanuatu and a common reason for hospital admission (VMOH, 2012; VMOH, 2010). '*Communicable diseases associated with poor sanitation continue to contribute significantly to disease burden*' (VMOH, 2012, p. 1). Areas with higher population densities and poor sanitation are of major concern since '*an outbreak of communicable water borne disease can quickly spread and affect a large number of people*' (UNESCO, 2012, p. 2).

A comprehensive database of water quality is lacking. Monitoring and surveillance is undertaken infrequent, records are bad, and information gained is rarely made available for other policy makers. The groundwater quality in and around Port Vila was tested more than twenty years ago and detected slightly elevated nitrogen levels and raised levels of faecal coliform bacteria in peri-urban areas. Records of surface water quality testing are poor too, but monthly sampling data from Tagabe River (Port Vila watershed) is available (SOPAC, 2007). These measurements revealed '*high levels of bacteria from human waste, and high COD* [i.e. chemical oxygen demand] *and nitrogens from industry and human waste*' (SOPAC, 2007, p. 19).

Statistics about the sanitation coverage compiled in the past do not comply with the official classification by JMP, making the data not or only badly comparable on national level and to other countries. In the MDG Report from 2010, Vanuatu classified improved toilet facilities such as '*flush, water seal and Ventilated and Improved Pit (VIP) toilets, whether shared or not* [as improved, and …] *pit latrines, any 'other' form of toilet and not having a toilet* [as not improved]' (VNSO, 2011b, p. v). On the other hand, data sampled during the Multiple Cluster Survey 2007 is divided in pit latrines with and without a slab, but it is not discerned between shared and private facilities. Based on this data, 63.5% of household members used improved sanitation facilities (urban: 91.1%, rural: 55.1%) (VMOH, 2008). An estimate by the JMP from 2012 comes up with similar figures, as it classifies 58% of Vanuatu's sanitation facilities as improved (urban: 65%, rural: 55%), 20% as improved but shared, 20% as unimproved, and the remaining 2% as open defecation (WHO & UNICEF, 2014a). The latest data from the 'Demographic and Health Survey 2013' (data basis: 2200 households) uses the official JMP classification of improved facilities for the first time (Table 4). This data reveals a different picture, by determining the households with access to improved sanitation by 50.7% (urban: 45.8%, rural: 52.7%) (VNSO, 2014). Rural areas rely mainly on pit-based sanitation. Unimproved facilities are primarily determined by shared facilities and pit latrines without slab/open pit (i.e. called 'Bush Toilet' in Vanuatu). Water-based facilities are dominating urban areas (septic tanks) where shared facilities are common.

Table 4: Main toilet facility used by households in rural and urban areas in alignment with the classification of improved and non-improved facilities by JMP (VNSO, 2014, p. 22, adapted).

Type of toilet	**Households [%]**		
	Rural	**Urban**	**Total**
Improved, not shared facility (subtotal)	(52.7)	(45.8)	(50.7)
Flush/pour flush to piped sewer network	1.4	6.6	3.0
Flush/pour flush to septic tank	2.8	29.8	10.9
Flush/pour flush to pit latrine	2.9	2.0	2.6
Ventilated improved pit (VIP) latrine	13.8	2.9	10.5
Pit latrine with slab	31.8	4.5	23.7
Non-improved facilities (subtotal)	(46.4)	(53.5)	(48.5)
Any facility shared with other households	18.7	48.0	27.4
Flush/pour flush not to sewer/septic tank/pit latrine	0.0	0.3	0.1
Pit latrine without slab/open pit	25.2	4.0	18.9
No facility/bush/field	2.5	1.2	2.1
Other	0.4	0.0	0.3
Total[1]	100.0	100.0	100.0

[1] Total percent may not add up to 100 due to rounding off or exclusion of 'missing' cases.

Statistics about sanitation available from 'Vanuatu National Population and Housing Census 2009' are not aligned with JMP's definition too, but the data is of interest since its sample size is the total population and it gives a better understanding about shared facilities (Table 5).

Table 5: Main toilet facility used by households in rural and urban areas (VNSO, 2011b, p. 177, adapted).

Type of toilet		Households [%]		
		Rural	Urban	Total
Flush	Private	5.3	43.3	14.6
	Shared	1.3	22.3	6.4
Water Sealed	Private	6.1	3.4	5.4
	Shared	2.3	6.3	3.3
VIP	Private	17.2	5.7	14.4
	Shared	8.4	6.5	7.9
Pit Latrine	Private	46.4	7.8	36.9
	Shared	12.2	4.6	10.3
None		1.0	0.1	0.8
Total		100	100	100

The classification does not distinguish between pit latrines with (i.e. improved) and without proper slabs (i.e. unimproved), reducing its comparability that way. Nonetheless, 58.6% of rural households depend on pit latrines and 25.6% use VIPs. This sums up to 84.2% of rural households relying on pit-based latrines as opposed to 24.6% in urban areas. Water borne facilities are secondary in rural (15.0%) as compared to urban areas (75.3%) (VNSO, 2011b).

'[A]ccess to improved sanitation systems depends more on the geographic location, less on the vulnerability status [in terms of poverty]' (VNSO, 2013, p. 15). Figure 4 shows this geographic dependence and high variability of used systems. The majority of households in the provinces of Penama, Torba and Tafea use pit-based toilets (95.4%, 94.0% and 93.4%, respectively) (VNSO, 2011b). Over 60% of households in Malampa and Penama use 'Bush Toilets', i.e. lack a slab (VMOH, 2008).

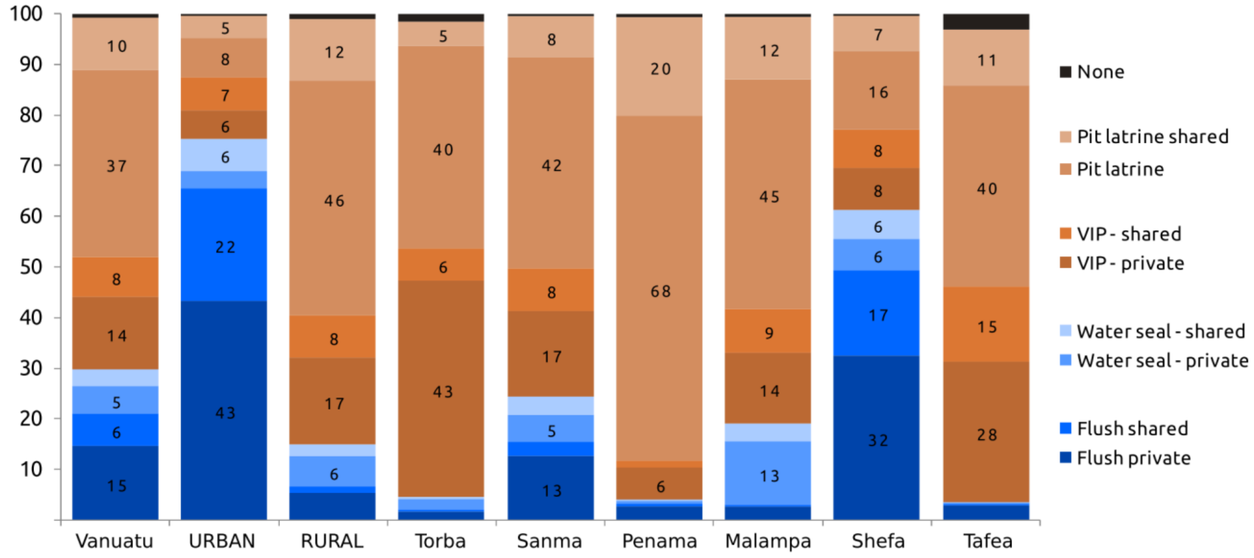

Figure 4: Main toilet type facility of Vanuatu's provinces, urban and rural areas (VNSO, 2011a, p. 140, adapted).

4. Fundamentals of cost analysis

4.1 Background

For many years, cost estimates in the Water, Sanitation and Hygiene (WASH) sector were often based on the WHO figures published in 1984. These show the total one-time, per capita costs for urban and rural water supply and sanitation facilities. Both hardware (e.g. infrastructure), and software costs (e.g. hygiene training or project design) were included in the estimates. Although many other cost estimates were created in the following years, the WHO figures were regarded as benchmarks for planning and budgetary calculations. In the course of the Millennium Development Goals (MDGs) numerous reports tried to assess the costs to reach the target of halving the number of people without access to safe water and sanitation facilities. Many of these global estimates were still based on the old figures from 1984, which had not been adjusted for country context or inflation (McIntyre et al., 2014). These generalised estimates are usually contentious, since they are based on several assumptions (e.g. the service level being provided). Obviously, there is a difference in the service level between a Single Pit Latrine and a connection to a sewer network with subsequent treatment. These universal figures can only give an indication of potential costs, but for planning purposes on a project or programme scale, a detailed estimation for every case is necessary. Further it is important that the cost estimation do not only include the initial one-off payment, but additionally the long-term expenses for operation and maintenance (Evans & Mara, 2011). This becomes particularly clear when looking back at the so called 'first water decade', in the 1980s. During this decade, sanitation was provided for almost 77 million people. However, development efforts were often solely concentrated on raising modern infrastructure. The consequence was that these achievements were temporary only and, for example, toilets were often abandoned when full. This trend continued in the second water decade in the 1990s. By continuously trying to extend the sanitation coverage where it did not exist, the necessity to sustain services that were already there, was often neglected. The result was high reoccurring costs for delivering the same infrastructure to the same communities. In the MDGs this problem was addressed by focusing on the effective use of financial resources. But still the information about the overall costs for WASH interventions, especially the costs of sustaining services, was limited (McIntyre et al., 2014).

In contrast to the MDGs, the concept of sanitation service levels focuses on the idea that sanitation must be delivered as a service and not as a one-off infrastructure investment. Hence all costs incurred over the whole lifetime of a system are included, in order to sustain a level of service. Table 6 depicts four different service levels for sanitation systems. The classification allows an assessment along the entire sanitation delivery chain, including: containment, collection/transport, treatment, disposal and reuse. Each service level parameter can only be met where all indicators are fulfilled. Further the principle was established, that the overall service level is determined by the lowest composite indicator (Potter et al., 2011). The suitability and service level of a sanitation technology is highly context specific, as Potter et al. (2011, p. 18) state, *'[…] a well operated and maintained VIP is arguably a higher level of service than a badly maintained septic tank system or a full flush system with inadequate water supply.'*

Beside the costs for initial investment, operation and maintenance, sanitation interventions also require auxiliary costs for management, regulation, surveillance, education and promotion. Project planning is often characterized by trade-offs between these costs, for example capital costs versus operational costs. The total costs for sanitation interventions might appear high, but the achieved benefits are usually significantly higher (Evans & Mara, 2011). *'Although improvements in sanitation are known to result in large economic benefit for society as a whole, the priorities of those who are responsible for investment, whether at the household, municipal or national government level, tend to set investment priorities differently, based on financial constraints and self-interest'* (Parkinson et al., 2012).

Table 6: Sanitation service levels with parameters and detailed indicators (Potter et al., 2011, p.19).

	Accessibility	**Use**	**Reliability**	**Environmental protection**
Improved service	Each family dwelling has one or more toilets in the compound Easy access for all family dwellings	Facilities used by all household members	Regular or routine O&M (including pit emptying) service requiring minimal effort Evidence of care and cleaning of toilet	Non problematic environmental impact/ Safe disposal and re-use of safe by-products
Basic service	Cement or impermeable slab at national norm distance from households (per household or shared)	Facilities used by some household members	Unreliable O&M (including pit emptying) requiring high level of user effort Evidence of care and cleaning of toilet	Non problematic environmental impact/ Safe disposal
Limited 'service'	Platform without impermeable slab separating faeces from users	No or insufficient use	No O&M (e.g. Pit emptying) taking place and no evidence of cleaning or care for the toilet	Significant environmental pollution, increasing with increased population density
No service	No separation between user and faeces, e.g. open defecation			

4.2 Approaches of cost analysis

Basically, it can be distinguished between economic and financial analysis for sanitation services. Beside decision making frameworks like the multi-criteria analysis, these analytical approaches represent a decisive part of policy decisions, sanitation programming and project design. By comparing costs and benefits of different sanitation interventions, decision makers can efficiently distribute limited resources and justify investments in sanitation in general. Financial analysis comprises only of costs and benefits that have direct and measurable financial consequences. Whereas economic analysis covers a broader spectrum of all costs and benefits, which go beyond direct financial implications (Parkinson et al., 2012). '*Economic analysis measures the broader welfare benefits of products and services on populations, such as value of life, time use, environmental and social benefits, as opposed to financial analysis, which measures the financial gains only (e.g., changes in income or cash situation)*' (Rodriguez et al., 2011, p. 1).

Setting a boundary for the analysis allows to allocate the input data either to the financial or economic analysis. A useful boundary can be set between the public and private domain, distinguishing which costs and benefits are allocated to the households on one side, and the project on the other side. Project costs are usually incurred by agencies or institutions, which promote or implement sanitation projects or programmes (Schuen et al., 2009).

4.2.1 Financial analysis

Financial analysis regards streams of expenditures and revenues (Parkinson et al., 2012). In other words, it '*[…] only considers subsets that are identifiable as financial transactions'* (Schuen et al., 2009, p. 3). As mentioned above the financial transactions must be analysed beyond the initial investment costs and further include recurrent costs for operation and maintenance. Thereby it is possible to compare the long-term costs of different sanitation options. In the course of a financial analysis it can be distinguished between the following cost elements (Parkinson et al., 2012):

- capital expenditure (CapEX)
- operational expenditure (OpEx)
- capital maintenance expenditure (CapManEx)

CapEx are one-time costs for the construction of fixed assets (e.g. concrete substructure) when a system is built or enhanced (Franceys & Pezon, 2010). It consists of costs for hardware, waste collection, transport and treatment facilities. It further includes costs of labour and management for planning, construction and work supervision. The capital costs are a crucial component of the purchase decision of potential sanitation technologies. Poor households are very sensitive to price in their decisions, especially in case of sanitation, which is usually not perceived as vital issue (Parkinson et al., 2012). Beside hardware costs, CapEx also includes software costs for onetime work with stakeholders, like one-off capacity building (Fonseca et al., 2010).

OpEx includes the costs for the day to day operation and maintenance of a system or facility. These are recurrent costs for e.g. labour, emptying of pits or vaults, treatment costs in case of faecal sludge, cleaning materials and minor repairs. Further it includes the costs of software components for achieving community acceptance and behaviour change. These aspects are crucial for the uptake, compliance and sustainability of all sanitation systems (Parkinson et al., 2012). Hence it is important to consider the costs for *'[…] sanitation promotion and demand creation (e.g. social marketing), awareness and educational campaigns to promote improved hygiene and system use, and capacity development of stakeholders (such as training of artisans, operators and sanitation suppliers)'* (Parkinson et al., 2012, p. 3). Most estimates calculate OpEx between 5% to 20% of the capital investment (CapEx) (Fonseca et al., 2011).

CapManEx comprises all costs for maintaining a constant service level by reducing the risk of asset failure. This is achieved by replacing, renewing, rehabilitating or refurbishing broken system parts (Parkinson et al., 2012). It includes everything that goes beyond routine maintenance work to keep the system running (Fonseca et al., 2011). The objective is to sustain a service at the same level at which it was initially delivered (see Figure 5). This generates occasional costs, usually after some years of operation (Franceys & Pezon, 2010). The importance of CapManEx is reflected in the sustainability of a system: *'When there is no timely capital maintenance expenditure the quality of services tends to decrease over time, in some cases leading to complete failure'* (Franceys & Pezon, 2010, p. 3). The costs for complete rehabilitation after a service failure are usually higher than the sum of the occasional CapManEx. Additionally, the users are left without an adequate service during the downtime of the system (Franceys & Pezon, 2010).

The allocation of costs to the different segments can be challenging. In case of OpEx and CapManEx the distinction can be made according to frequency (OpEx occur more often than once per year) and amount (CapManEx are significant higher in comparison to recurring OpEx) (Franceys & Pezon, 2010). According to the terminology of IRC's WASHCost project other cost categories, like 'cost of capital' or 'expenditure on direct and indirect support' can be distinguished (Fonseca et al., 2010). Due to lack of data these cost categories are not considered in the subsequent calculation of this thesis.

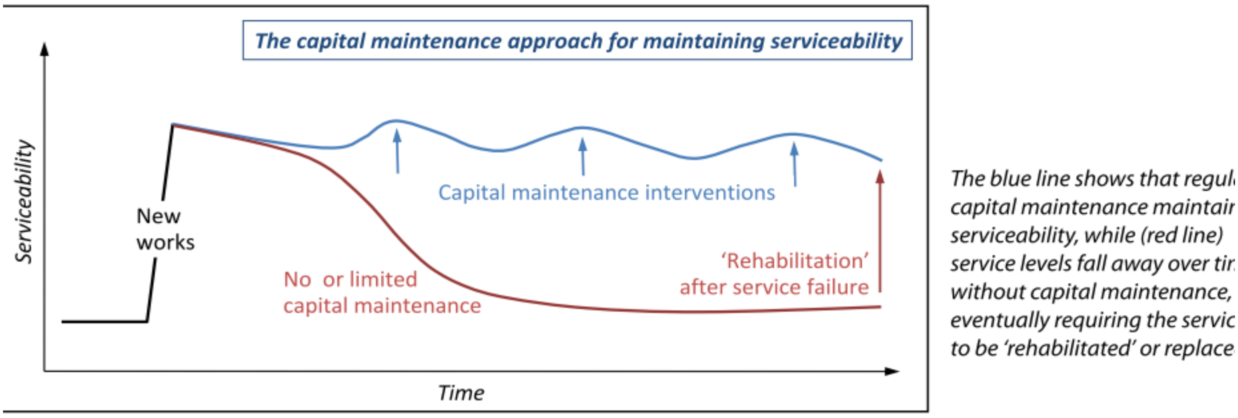

Figure 5: Effect of CapManEx on the serviceabiltiy of a system (Franceys & Pezon, 2010, p. 3).

4.2.2 Economic analysis

The economic analysis is based on the results of the financial analysis and further expands the scope to cover social and environmental costs and benefits. Hence in addition to the financial cash flows it also includes in-kind or external costs and benefits, which can be described with monetary values (Parkinson et al., 2012). In contrast to financial costs, which must be financed with cash, economic costs also account for in-kind contributions with labour or materials. A valuation of the so called 'shadow price' for own labour can be done using the price of local non-qualified labour. The sum of the financial and non-financial costs presents the opportunity costs. These refer to the opportunity lost from spending cash, labour effort and materials for sanitation rather than for some other productive use (Hutton et al., 2009).

The benefits of improved sanitation, assessed in an economic analysis, are related to the following aspects: health benefits (e.g. avoided morbidity and deaths), economic benefits (e.g. fewer sick days, time savings through decreased distance or waiting time for shared facilities), environmental benefits (e.g. reduced water pollution), benefits of reusing excreta (e.g. fertiliser), wider economic benefits (e.g. increased attractiveness for tourism or business). Further there are other benefits which are very difficult to monetize, like improved living quality through increased privacy, dignity, convenience and status (Parkinson et al., 2012). In general, quantifying sanitation impacts and converting them into monetary figures is a challenging task. On the one hand, improved sanitation is usually one of many simultaneous development efforts generating a positive socio-economic impact, which makes it difficult to attribute the achievements to a specific intervention. On the other hand, the process of monetization increases the uncertainty of the already uncertain assessment of sanitation benefits, due to factors like highly variable prices or imperfect markets. In addition, prices for some of the sanitation benefits (e.g. comfort value) do not exist at all and must be determined via proxy pricing or contingent valuation techniques. A full economic analysis is only possible where reliable data from robustly designed studies are available. Hence extensive research for a full economic analysis, considering all costs and benefits, is only justified for larger programmes (Hutton et al., 2009). Due to a lack of data these benefits cannot be included in the following calculation.

5. METHODS

5.1 LITERATURE RESEARCH

For the most part, this thesis is the result of a literature research. Plenty of information about sanitation in developing countries is accessible via scientific publications in journals, papers and reports from governments or non-governmental organisations. Most of these resources are available online and were gathered with search engines (e.g. BOKU:LITsearch, scholar.google.com). Additionally, portals for sanitation in developing countries (Susana.org, SSWM.info) or reference lists of research documents were used to obtain information.

Country-specific data about the South Pacific region and Vanuatu were sourced from the South Pacific Applied Geoscience Commission (SOPAC) and the Vanuatu National Statistics Office (VNSO).

Chapter 6 (Sanitation system analysis) is based on the classification of EAWAGs' *'Compendium of Sanitation Systems and Technologies'* by Tilley et al. (2014). The categorization of toilet technologies into eight different systems was a useful starting point for the analysis. Building on this structure each system was assessed against three evaluation criteria, particularly in regard of its suitability under the given conditions. By means of a literature-based comparison of the different systems, one option was identified for further analysis.

The GIZ technology review reports by Rieck et al. (2012) and Münch & Winker (2011) were key sources for the subsequent chapter 7 (Design aspects of the Urine-Diverting-Dry-Toilet system). Further case studies and reports from regions featuring similar challenges were included.

5.2 ON-SITE RESEARCH

Essential data and information were collected during two months of field research in Vanuatu (November & December 2015), comprising of:

- MEETINGS AND SEMI-STRUCTURED INTERVIEWS

  These were conducted with officials of the governmental department in charge of water supply (i.e. Department of Geology, Mines and Water Resources, DGMWR) and representatives of NGOs working in the WASH sector (i.e. Oxfam, Live&Learn, World Vision, Wan Smol Bag).

- ASSESSMENT OF FIVE COMPOSTING TOILET PILOT SITES
  - Tangovauwia school, Pele Island
  - Tagabe catchment, Blacksands, Efate (Salvabay and Paama community)
  - Sarakata catchment, Espiritu Santo (Pepsi and Solway)

  Weak spots in the design and construction of the facilities were identified through visual inspections and interviews with the owners or users, responsible for operation and maintenance tasks.

- IDENTIFICATION AND INSPECTION OF POTENTIAL PILOT PROJECT SITES ON EMAE, VANUATU

  Four villages were visited and evaluated in regard of the featured conditions (i.e. high groundwater table, flood proneness and limited water supply). Interviews with chiefs of these communities revealed problems of the current sanitation system and resulting needs and demands.

- COLLECTION OF DATA FOR THE FINANCIAL ANALYSIS

  The costs for construction materials were determined through inquiries to local hardware stores. Additionally, prices from local timber suppliers were obtained. Transport costs, labour costs and information concerning local building materials were gathered during the semi-structured interviews and conversations with inhabitants from Emae.

- INTRODUCTION OF UDDTS TO CHIEFS AND INHABITANTS OF FOUR COMMUNITIES ON EMAE

  Since this is a new sanitation approach for most people, the explanation and following discussions were useful to assess people's opinions and attitudes towards this unfamiliar technology.

5.3 FINANCIAL ANALYSIS

The financial analysis was conducted for both sanitation systems, the Single Pit Pour-Flush Latrine and the Urine-Diverting-Dry-Toilet (UDDT). Detailed design drawings were created with the 3D modelling software SketchUp. Subsequently Bills of Quantity (BOQ) for both systems, containing all construction materials as well as transport and labour costs were compiled in Microsoft Excel spreadsheets. These lists were the basis for the cost analysis. The cost data collected during the on-site research, as described above, were used for the calculation. The two systems were compared over a time period of 20 years, by discounting the future costs to a present value. This approach is briefly explained in the following.

To cover all costs and benefits over the total duration of a planned project, also called planning horizon, a life cycle analysis is required. The design life (estimated lifespan) of single components of a sanitation system can be smaller or larger than the planning horizon of the project. This depends on the type of component, the built quality and the selected planning horizon (Parkinson et al., 2012). If investment options are compared over an extended timeframe, then the 'time value of money' must be considered. This approach takes into account that the value of money available now is higher than the value of money in the future. Thereby the 'opportunity cost of capital', which show the likely return of using that money in the best alternative, are reflected in the calculation. Money available now can be used or invested to produce returns through interest. The Present Value can be estimated by discounting the future costs to the present. If not only the Present Value of future costs but also the estimated future benefits are considered in the analysis, then this approach is referred to as net present value analysis (Fonseca et al., 2011, briefing note 1a). *'The Net Present Value (NPV) of a project or investment is defined as the sum of all the present values of the annual cash flows during the life of the project, minus the initial investment. Annual cash flows are the net benefits (revenues minus costs) generated from the investment during its lifetime (Schuen et al., 2009, p. 19)'.* The applied discount rate should be based on the opportunity costs of capital in a given national economy. If there is no accepted national discount rate, then a discount rate of 5% is often used (Parkinson et al., 2012). Schuen et al. (2009) state that values between 8% and 12% are common practice on international level. Fonseca et al. (2011) recommend a discount rate of 10% for low income countries. The net present value can be calculated with the following equation (Boardman et al., 2018):

$$NPV = \sum_{t=0}^{n} \frac{B_t}{(1+i)^t} - \sum_{t=0}^{n} \frac{C_t}{(1+i)^t}$$

n = planning horizon (analysis period)
t = year
B_t = benefit in year t
C_t = cost in year t
i = discount rate

6. SANITATION SYSTEM ANALYSIS

6.1 EVALUATION CRITERIA

For the analysis of eight sanitation systems, the limitations as well as the requirements of a sanitation system are defined. Ensuing from the formulated problem statement by Oxfam (Andy Thompson) and the data about Vanuatu supporting these statements, the overarching limitations and requirements for the system are given in Table 7. These specified limitations narrow the scope of possible solutions and are the basis for the subsequent selection. In general toilets must safely contain the excreta and prevent negative implications for the users and the environment. Considering the drinking water scarcity, the protection of precious groundwater resources should be ensured in order to diversify possible drinking water sources. In view of recurrent flood events, the sanitation system should minimize the imminent risk of pathogens being spread in the environment. Moreover, to avert open defecation, accessibility of the facility during and after floods should be ensured.

Table 7: Limitations and requirements for the sanitation system.

Limitation	Requirements
High groundwater table	Prevention of groundwater contamination
Prone to floods, natural disasters & rising sea level	Operability and safe containment of excreta during and after flood events
Insufficient water supply	No or low water demand

These three limitations are subsumed in the main evaluation criteria APPLICABILITY (I, see below), a potential system must fulfil. A system will be excluded if one or more of these limitations are not fulfilled. Furthermore, three secondary criteria (II OPERATION & MAINTENANCE, USER ACCEPTANCE; III FURTHER CONSTRAINTS & RISKS; IV FURTHER ADVANTAGES) are included in the analysis to identify one system to be examined in more detail.

I. APPLICABILITY

a. High groundwater table

The system must be applicable in areas with high groundwater table, ensuring to prevent this potential source of drinking water from being contaminated with faecal pathogens.

b. Flood resilience

The system must be accessible and operable during and after flood events to avert open defecation. Excreta must be contained safely without the risk of being spread in the environment.

c. Water dependency

A system's reliance on water constitutes a major constraint due to the lack of water supply.

II. OPERATION & MAINTENANCE, USER ACCEPTANCE

a. Operation & maintenance

Needed knowledge, facilities (e.g. for further treatment), resources (e.g. additives, time, electricity) and infrastructure (e.g. roads for vehicular access).

b. User acceptance

User acceptance of the system, O&M etc.

III. FURTHER CONSTRAINTS & RISKS

e.g. remarkable complexity of construction, inadequate pathogen containment/ removal, environmental impacts

IV. FURTHER ADVANTAGES

e.g. reuse of urine or faeces

6.2 DESCRIPTION AND EVALUATION OF SANITATION SYSTEM

6.2.1 SINGLE PIT SYSTEM

OVERVIEW

- DESCRIPTION: A common Single Pit or Single Ventilated Improved Pit (VIP) system consists of pit dug in the ground and a toilet positioned on top to collect, store and partially treat excreta. If the pit is full, a new one is dug, or it has to be desludged and treated before it is disposed of.
- USER INTERFACE: Dry Toilet or Pour-Flush Toilet
- INPUTS: Urine, faeces, dry cleansing materials or anal cleansing water and / or flushwater
- AREA OF APPLICATION: Needs enough space for digging new pits or regular emptying; best suited for rural and peri-urban areas; soil has to be suited for digging pits & absorbing leachate (Tilley at al., 2014).

EVALUATION AGAINST CRITERIA

I. APPLICABILITY

a. High groundwater table

Falkland (2002, p. 24) assesses pit latrines as *'inappropriate sanitation systems'* for small island countries (note: the author does not distinguish between waterless and water-based systems). In general, pit latrines can lead to a contamination of groundwater and surface waters with viruses and bacteria. Nitrate contamination of the groundwater is another crucial concern of pit-based systems (Stenström et al., 2011). The ARGOSS report (2002, p. 32) states, *'[w]hilst microbiological contamination is perhaps of more immediate concern, nitrate represent a more persistent problem in the longer term'.* The risk for groundwater pollution is highest in areas with high water tables and prone to floods, due to the importance of the vertical separation between the bottom of the pit and the saturated zone (Graham & Polizzotto, 2013). *'The soil is the main zone in which surface pollutants are attenuated. However, pit latrines place the pollutant below this zone and so the unsaturated zone represents the first line of natural defence'* (Argoss, 2002, p.10). As a rule of thumb, the minimum distance between the bottom of the pit and the groundwater table is supposed to be 2m. Nevertheless, this is influenced by the permeability of the unsaturated zone and is therefore dependent on the prevalent grain size, moisture content and other environmental factors (ARGOSS, 2002; Tilley et al., 2014). Beside seasonality (wet or dry season) the local geo- hydrological conditions (e.g. fractured rocks, soil with high porosity or high groundwater level) are the main determinants of the scale of groundwater pollution (Stenström et al., 2011). The aim of conventional pit latrines is to hold back the solid fraction and infiltrate the liquids into the sub-soil. However, the liquids wash out the soluble elements of the excreta including pathogens, which may result in groundwater contamination (Werner et al., 2004). The liquid part inside a pit, which infiltrates into the surrounding soil is referred to as hydraulic load. If the hydraulic load is high and exceeds the natural attenuation potential of the sub-surface soil, then a direct contamination of groundwater resources can occur (ARGOSS, 2001). The hydraulic load of Dry Pits is substantially reduced in comparison to water sealed systems. This results in a low or even absent static head, limiting the pressure towards the flow to the unsaturated zone (Sugden, 2006). Sugden (2006, p. 2) states the general rule: *'The smaller the amount of liquid in the pit, the lower the risk of water point contamination'*. A major problem in areas with high water tables is raised by the fact, that pits are often dug till the water table is reached, leading to a direct contamination of the groundwater (Falkland, 2002; UNEP, s.a.). A study from the Asian Development Bank, assessing the water and sanitation situation in Kiribati, states, *'[t]hin porous atoll soils […] make groundwater highly vulnerable to contamination from human and animal wastes'* (ADB, 2014, p. 1). Although Pour-Flush Pit Latrines are defined as 'improved sanitation' by the Joint Monitor Program of UNICEF and WHO, *'[…] in Kiribati, given the fragile atoll environment, some improved sanitation options, such as the pit latrines, have the potential to contribute to water borne diseases. Pit latrines discharge directly into the shallow freshwater lens, resulting in contamination of groundwater supplies'* (ADB, 2014, p. 7). Tilley et al. (2014) recommend using this system for areas with low water tables, nevertheless pits can be raised to be more applicable if the groundwater is high. The lining of the pit can be extended above ground. Usually this increases the costs, as the above ground lining has to be sealed and reinforced with an earth mound, to prevent seeping of the pit content through the side walls, if infiltration below ground is insufficient (Franceys et al., 1992). According to Mbuligwe & Kaseva (2005), raised pits even increase the potential of groundwater and surface water pollution, due to a higher hydraulic gradient of the pit content compared to the surrounding area. *'Also, the ponding that occurs around the pit can raise the groundwater table to above the ground level. When it rains, the outcropping groundwater, which is essentially pit latrine effluent, is washed away with runoff […]'* Mbuligwe & Kaseva (2005, p. 7). Further pits can be sealed to be apt under this condition (ARGOSS, 2001; Graham & Polizzotto, 2013). However, sealed pits require desludging. In Vanuatu, desludging services are only available in Port Vila on the main island, but these are too expensive for most of the inhabitants (Castalia, 2005). In rural areas there are no desludging services and since there is usually enough space, it is common practice to abandon full pit toilets and dig new ones instead (Kassis, 2010). Usually these toilets are very basic Single Pits without a proper slab, which are referred to as 'Bush Toilets'.

b. Flood resilience

Pits can overflow, when built in areas prone to flooding or heavy rainfall (Tilley et al., 2014). Kassis (2010) states that on Efate (Vanuatu) during heavy rainfalls pits often overflow and run off into the adjacent Teouma river. Overflow and leaching can result in serious health and environmental problems. Research from flood prone areas in Bangladesh, where pit latrines are the most common form of sanitation and also the most vulnerable to flooding, show the adverse effects of floods. Beside health risks and risks of environmental contamination, pit latrines are also inaccessible during the flood, which may cause open defecation. The latrines often remain inaccessible even after the inundation phase, due to the large amount of silt that accumulates in the structure during the event. Furthermore, pits are prone to collapse when flooded (Uddin et al., 2013). Moreover, facilities for further treatment of the sludge can be rendered inoperable or even destroyed by a flood (Sherpa et al., 2014). *'To prevent groundwater pollution and increased health risks, pit toilets are only suitable in flood-free areas, where the highest seasonal groundwater table lies well below the floor of the pit'* (Gutterer et al., 2009, p. 286). Raising the pit with concrete rings and blocks can be an alternative for flood prone areas (Tilley et al., 2014).

c. Water dependency

Depending on the preferred User Interface, this system can be operated without (Dry Toilet) or with (Pour-Flush Toilet) flushwater (Tilley et al., 2014).

II. OPERATION & MAINTENANCE; USER ACCEPTANCE

a. Operation & Maintenance

Various options are possible when the pit is full. A common approach is to remove the faecal sludge and transport it to a further treatment facility (e.g. sedimentation/thickening, unplanted drying bed, co-composting and/or biogas reactor). The emptying and transport are done either by human labour or with motorized machineries. Several potential technologies are used for emptying pit latrines. The most common one is the vacuum truck, which requires road access. Other technologies range from manual emptying with simple hand tools over manual hand pumps to mini-vacuum tankers (Thye et al., 2009). Another option is to transport the superstructure, ring beam and slab to a new site, abandon the old pit and simply fill and cover it with soil. Alternatively, a tree can be planted on top of the decommissioned pit, which is then referred to as Arborloo. These shallow, dry pits are used for approximately 6 to 12 months. Afterwards the tree can make use of the nutrients from the degrading pit content. Since the Arborloo is a dry pit system, a cup of soil or ash should be put on the faeces after defecation. Occasionally adding leaves enhances porosity and air content in the pile. If the pit is covered and marked properly the risk of infections and pathogen transmission is low as the users do not come in contact with the faecal matter. As over time the content is decomposed naturally in the soil, no immediate health risks are present. Nevertheless, under certain conditions (e.g. waterlogged soil) the abandoned pit is a potential source for groundwater contamination. The Fill and Cover / Arborloo option is feasible if the following conditions are met: There must be enough space available to continuously dig new pits when the old ones are filled up. The superstructure, ring beam and slab must be moveable in order to transfer them to the site of the new pit (Tilley et al., 2014; Stentröm et al., 2011). In Vanuatu Fill and Cover is the most common method for disposal of pit-based systems (Kassis, 2010). According to the SOPAC report of Vanuatu (2007, p. 36) *'[...] there is serious concern over the poor construction, inappropriate siting, inadequate supply, and poor maintenance of pit style latrines.'*

b. User acceptance

Single Pit systems are the most common sanitation option in Vanuatu (VNSO, 2014). Hence it can be assumed that the user acceptance of the system is high. In general, users prefer more convenient systems, so called 'drop-and-forget' systems, such as flush toilets which are supposed to be the most desired option in Vanuatu (Rieck et al., 2012; Crennan & Booth, 2007).

III. FURTHER CONSTRAINTS & RISKS

Water inside the pits facilitates insect breeding. Further smell and odour might be perceivable. These problems can be overcome by upgrading the system with a ventilation pipe (VIP). Besides, the maintenance costs, especially the costs for emptying pits, can be significant (Tilley et al., 2014; Monvois et al., 2010). Furthermore, greywater should not be discharged to the pit. Large amounts of greywater may result in excessive leaching and a shorter lifespan of the pit. Moreover, the reduction rate of BOD and pathogens in pit latrines is low, depending on soil types, travel distance, soil moisture and other environmental factors (Tilley et al., 2014). The door of a VIP has to be shut all the time to guarantee darkness in the cabin that flies are attracted by the vent pipes light. Children may be afraid of using the toilet because it has to be kept dark inside (Brikke, 2000).

IV. FURTHER ADVANTAGES

Constructing pit latrines is simple and requires little space. The Single Pit system is one of the least expensive concerning the capital cost for construction. Furthermore, they can be built with locally available materials. If the ground is appropriate, the pit can be dug very deep, what can extend its lifetime to more than 20 years (Tilley et al. 2014; UNEP 2002).

6.2.2 WATERLESS PIT SYSTEM WITHOUT SLUDGE PRODUCTION

OVERVIEW

- DESCRIPTION: In case of a Double Ventilated Improved Pit or a Fossa Alterna system two alternating pits allow desiccation and degradation of the pit content. Thereby the material gets transformed into Pit Humus (earth-like substance), which is fairly safe to handle. When one pit is full, it gets covered and has time to rest until the second pit is almost filled up. Then the material in the first pit gets excavated and can be used as soil conditioner. Double-Vault Composting toilets also work with two alternated vaults, where excreta are supposed to be treated through composting processes. Composting chambers (single vault continuously operated) are not included due to the sophisticated design and operation, which are not suitable in this context.
- USER INTERFACE: Dry Toilet or Urine-Diverting-Dry-Toilet, Urinal (optional)
- INPUTS: Urine, faeces, organics (restricted, optional), dry cleansing or anal cleansing water, cover material
- AREA OF APPLICATION: Can be applied in areas with limited space as well as densely populated areas due to continuous emptying (Tilley et al., 2014).

EVALUATION AGAINST CRITERIA

I. APPLICABILITY

a. High groundwater table

The applicability of a Double VIP as well as Alternating Pits (Fossa Alterna) in areas with high groundwater tables is comparable to a Single VIP using a Dry Toilet User Interface (see Single Pit, 6.2.1). Nevertheless, the depth of a Double VIP as well as Fossa Alterna can be reduced in comparison to a Single Pit (Tilley et al., 2014; Stenström et al., 2011). The soil layer between the bottom of the pit and the water table is therefore likely to be thicker compared to a Single Pit with a Dry Toilet User Interface. This may result in a lower potential of groundwater contamination through leachate because *'[...] the faecal matter is contained within the biologically active upper soil zone, where it can be decomposed'* (Gutterer et al., 2009, p. 287). Hence, *'[s]hallow pits are an intermediate alternative [in between Pit latrines and elevated toilets, collecting the excreta above ground] and limit groundwater contamination'* (Schönning & Stenström, 2004, p. 8). Composting Toilets exist in various designs. They are usually built above ground, often with alternating, watertight vaults similar to Urine-Diverting-Dry-Toilets (Gutterer et al., 2009). Hence composting toilets are applicable in areas with a high groundwater table. Nevertheless, depending on the design, leachate may infiltrate into the ground (Tilley et al., 2014).

b. Flood resilience

Since Double VIP and Fossa Alterna are pit-based, they are not suitable for flood-prone areas (see Single Pit, 6.2.1) Due to the fact that Composting Toilets are built above ground with watertight vaults, they can be used in flood-prone areas (Calvert, 2013).

c. Water dependency

This system is independent from water per definition (Tilley et al., 2014).

II. REQUIREMENTS FOR OPERATION & MAINTENANCE; OVERALL USER ACCEPTANCE

a. Operation & maintenance

Operation and maintenance are of high importance for a well working system. All three storage and treatment facilities need to be emptied. Alternating pits have to be excavated more often (once per year or every two years), but this is easier due to the shallow pit and less compact contents. Depending on the vault size the chambers of Composting Toilets have to be emptied every 2-10 years and Double VIPs after several years. When the pit of a Fossa Alterna or a Double VIP toilet is full, the superstructure and/or the interface have to be moved and the out-of-service pit has to be covered properly. Fossa Alterna requires constant availability of cover material (e.g. soil, ash or leaves). There is no need and no costs for further treatment of Fossa Alterna's and Double VIP's end products. If there are hygienic concerns, it can be further composted or simply disposed of. Regular cleaning of the vent-pipes' screen (removal of webs, dead flies etc.) is required to ensure good ventilation. Facilities for further sludge treatment are not necessary, hence road access is not needed (Tilley et al., 2014).

In case of composting toilets, the treatment relies on a composting process with thermophilic, aerobic bacteria and fungi. Thermophilic organisms flourish at temperatures between 45-80°C, and mesophilic organism between 15-40°C. Organic matter is biologically degraded, which increases the temperature in the pile. Depending on the conditions the temperatures in the heap may rise to 50–70°C, resulting in a substantial pathogen reduction (Berger, 2011). In case of composting, heat treatment is considered the most effective way of pathogen inactivation. Sanitization can be depicted as a function of temperature over time. If a certain temperature-time relation is reached in the entire pile, then the material can be considered microbiologically safe for handling and reuse in agriculture (Schönning & Stenström, 2004). However, to achieve the required temperatures in the pile, the following conditions must be sustained: (1) good aeration to ensure continuous oxygen supply, (2) appropriate moisture content between 45-65%, and (3) adequate carbon-to-nitrogen ratio (C/N ratio) of 30-40 / 1. If only human excreta and food waste is added to the vault, then these conditions cannot be attained as the water and nitrogen content would be too high. Hence it is required to regularly add bulking material (e.g. ash, saw dust, pieces of paper) to decrease moisture, improve aeration and increase the carbon content in the heap (Berger, 2011).

In practice it may be difficult to meet these complex conditions within the composting vaults. Hence temperatures may not reach more than 40°C and thus remain in the mesophilic range (Berger, 2011). A study by Redlinger et al. (2001) shows that temperatures for aerobic thermophilic bacteria growth were almost never achieved due to multiple reasons. On the one hand small volumes of material cannot trap sufficient heat. On the other hand, they observed failures in operation, like wrong moisture levels or insufficient oxygen content due to not turning over or stirring the pile regularly. Hill and Baldwin (2012, p. 1813) state that *'[t]hermophilic temperatures are seldom if ever attained eliminating this reliable mechanism of pathogen destruction'.* Pathogen reduction can be accomplished, but a pathogen free material cannot be guaranteed (Berger, 2011). *'As a result, the output product is often not sufficiently stabilized and sanitized, and requires further treatment*' (Tilley et al., 2014, p. 72). Composting toilets, which operate at a mesophilic temperature range, achieve pathogen reduction to variable extents. A thermophilic composting process is mainly accomplished in large, properly maintained and well-insulated composting units. It is therefore not recommended to solely rely on this treatment method on a domestic scale. Rather it should be combined with other barriers or processes of pathogen inactivation (i.e. secondary composting, long term storage, high pH-value, UV light exposure) (Schönning & Stenström, 2004; Berger, 2011).

A well-functioning compost toilet, which relies on thermophilic composting, requires strong commitment and skilled management from the operators or users (Berger, 2011; Schönning & Stenström, 2004). According to Hill et al. (2013, p. 30) *'numerous composting toilet studies indicate a failure to produce sanitized material […] due to a variety of causes including: poor design, overuse, insufficient maintenance, low temperatures, anaerobic conditions, and excessive urine'*.

A review of the rural sanitation program in Vanuatu by Stitt (2005, p. 2) stated, that *'[i]t can be assumed that composting toilets cannot currently be implemented because they require an advanced understanding of latrine maintenance and high personal finances* *(for material transport [for the construction]) not yet held by the majority of the rural population of Vanuatu'*.

b. User acceptance

In general, users prefer more convenient systems, so called 'flush-and-forget' or 'drop-and-forget' systems, such as flush toilets which are supposed to be the most desired option in Vanuatu (Rieck et al., 2012; Crennan & Booth, 2007). Depending whether compost is used as fertilizer or not, there can be constraints regarding the acceptance of using decomposed human waste as fertilizer, but it can be disposed of alternatively (Rieck et al., 2012). It is time intensive and complicated to gain acceptance for a newly introduced type of sanitation system like compost toilets (Crennan & Booth, 2007; UNEP, 2002). In trials of implementing composting toilets in SIDS, people have often been critical at first but accepted the technology after experiencing its benefits (UNEP, 2002). Field research has shown that handling and reusing faecal waste should not be a problem for NiVans.

III. FURTHER CONSTRAINTS & RISKS

The collection and treatment of greywater must be done separately (Monvois et al., 2010; Tilley et al., 2014). The door of a VIP has to be shut all the time to guarantee darkness in the cabin that flies are attracted by the vent pipes light.

IV. FURTHER ADVANTAGES

Flies or other insects and odours are reduced significantly in comparison to toilets without ventilation (Brikke, 2000; Tilley et al., 2014). The system is permanent and can be used indefinitely. After adequate post-treatment, the end-product (i.e. pit humus or compost) may be used as soil conditioner with fertilising qualities. Additionally, it improves the water-holding capacity of the soil (Berger, 2011; Tilley et al., 2014). Excavation of humus or compost can be done manually and is easier than systems producing faecal sludge. Dry cleansing material can be collected in the pits/chambers and can be beneficial if they are carbon rich (better aeration and degradation) (Tilley et al., 2014).

6.2.3 POUR-FLUSH PIT SYSTEM WITHOUT SLUDGE PRODUCTION

OVERVIEW

- DESCRIPTION: A Pour-Flush Toilet is placed above Twin Pits, which are used alternately. Due to the porous lining of the pit walls, liquids infiltrate into the surrounding soil and solids accumulate and degrade at the bottom of the pit. When a pit is full, it gets covered and the other pit gets put into service. After a minimum resting phase of two years the material in the first pit should have been degraded into Pit Humus and is ready for excavation.
- USER INTERFACE: Pour-Flush Toilet
- INPUTS: Urine, faeces, flushwater, anal cleansing water, dry cleansing materials, greywater
- AREA OF APPLICATION: Rural & peri-urban areas as long as soil is suitable for absorbing the leachate (Tilley et al., 2014).

EVALUATION AGAINST CRITERIA

I. APPLICABILITY

a. High groundwater table

The applicability of this system in areas with shallow groundwater is comparable to a Single VIP using a Pour-Flush Interface (see Single Pit, 6.2.1).
Since two pits are used, the depth of Pour-Flush Toilets with Twin Pits is lower compared to a Single Pit water-based system (Gutterer et al., 2009). This results in an increased distance between the bottom of the pits and the water table.

The system requires soils that can continually and properly absorb the leachate. Therefore, the systems performance depends on soil conditions and the ground water level. If the groundwater table is too high, then the dewatering process will be impaired and groundwater contamination is possible. The potential for groundwater contamination is higher in comparison to Dry Pit Latrines, due to the increased amount of water that leaches out of the pit. Hence, the system is not appropriate if the groundwater table is shallow (Tilley et al., 2014; UNEP, s.a.).

b. Flood resilience

Pit-based systems are not well suited for flood prone areas in general (see Single Pit, 6.2.1). Beside the common constraints of pit systems, the dewatering process in the resting pit will be affected negatively, when additional water is entering (Tilley et al., 2014).

c. Water dependency

The system relies on water and is therefore not suitable for all areas of Vanuatu. It's only appropriate when there is a constant supply of water available. However, the amount of water required for one flush is relatively small (2-3L). It's also possible to use recycled water or collected rainwater (Tilley et al., 2014; UNEP, s.a.).

II. OPERATION & MAINTENANCE; USER ACCEPTANCE

a. Operation & maintenance

Since the degraded material is dry, the humus-like substance can be removed manually, which is easier than excavating faecal sludge (UNEP, s.a.; Tilley et al., 2014). Compared to a waterless pit, the system may include more maintenance effort, due to the possibility that blockages are built up. Hence, dry cleansing materials should be disposed of separately to avoid blocking of the pipes (Tilley et al., 2014). No roads are needed for vacuum trucks to enter the site for desludging services (UNEP, s.a.; Tilley et al., 2014). Operation of the systems requires a regular transport of water to the toilet.

b. User acceptance

The overall user acceptance is usually high, because users do not see or smell the excreta from previous users (Tilley et al., 2014). In general, users prefer more convenient systems, so called 'flush-and-forget' or 'drop-and-forget' systems, such as flush toilets which are supposed to be the most desired option in Vanuatu (Rieck et al., 2012; Crennan & Booth, 2007). Depending whether dried pit content is reused or not, there can be constraints regarding the acceptance of using decomposed human waste as fertilizer, but it can be stored safely or disposed of alternatively (Rieck et al., 2012; Tilley et al., 2014).

III. FURTHER CONSTRAINTS & RISKS

Materials and skills, which may not be available locally, are needed for construction of the Pour-Flush user interface (Tilley et al., 2014).

IV. FURTHER ADVANTAGES

The final product can be applied as soil amendment for agricultural purposes. The degraded pit humus is more hygienic, therefore no further treatment is necessary, after a resting phase of minimum two years. The filling and emptying cycle can be repeated constantly. Furthermore, there is no need for adding soil or organic material to the pit. The system can cope with greywater, but the amount should be limited due to the risk of extensive leaching. A s-shaped water seal inhibits flies and odours to leave the pit through the pipe.

6.2.4 WATERLESS SYSTEM WITH URINE DIVERSION

OVERVIEW

- DESCRIPTION: The main characteristic of the system is the separation of Urine and Faeces from the very beginning. This allows a dehydration of the Faeces and results in a die-off of pathogens. Further the nutrient rich Urine can be reused as fertilizer. When two watertight vaults are used alternatingly, the dehydration period is extended.
- USER INTERFACE: Urine Diverting-Dry-Toilet, Urinal
- INPUTS: Faeces, urine, anal cleansing water, dry cleansing & cover material
- AREA OF APPLICATION: Can be used anywhere (Tilley et al., 2014).

EVALUATION AGAINST CRITERIA

I. APPLICABILITY

a. High groundwater table

This system is suitable for areas with high groundwater tables because the vaults are constructed above ground level and are watertight (Brikke, 2000; Calvert, 2013; Rieck et al., 2012; Waste NL, 2006; Tilley et al., 2014; Uddin et al., 2013; Cruz et al., 2005; Fogde et al., 2011). If the urine is not reused entirely, it can be infiltrated into the soil via a soak pit or a subsurface leach field, alternatively it can be discharged into an Evapo-transpiration bed. Infiltration may have negative effects on the groundwater. The main concern is elevated levels of nitrate (NO_3) (Stenström et al., 2011).

b. Flood resilience

Due to its watertight design, it is apt for areas prone to floods (Calvert, 2013; Rieck et al., 2012; Waste NL, 2006; Morgan, 2009; Tilley et al., 2014; Uddin et al., 2013). This type of sanitation has successfully been implemented in flood prone areas, including the continual usability during floods (Sherpa et al., 2014). Rieck et al. (2012, p. 6) state, that this system has *'[…] a well-documented record of resilience during flood events. The sealed, aboveground vaults can be built above the established flood line and also returned to operation quickly when affected.'*

c. Water dependency

This system is water-free per definition (Tilley et al., 2014; Cruz et al., 2005).

II. OPERATION & MAINTENANCE; USER ACCEPTANCE

a. Operation & maintenance

Operation and maintenance includes separate collection and treatment of dry cleaning material, pushing the accumulated faeces below the toilet to the sides, providing cover material (soil, sand, ash, lime, leaves or compost) for applying it after each use, managing the accruing urine, removing spider webs and flies from the vent-pipe screen and emptying the vault (max. twice a year). Therefore, training of the users is required (Brikke, 2000; Tilley et al., 2014). As for most other systems, the proper long-term operation and maintenance of the system is a crucial aspect (especially the emptying of the chambers) (Crennan & Booth, 2007; Stitt, 2005). Roads for accessing the systems facility with vehicles are not necessary (Brikke, 2000; Tilley et al., 2014).

b. User acceptance

A constraint in terms of social acceptance is the fact that the toilet is usually raised above ground, what has been disliked in some Pacific countries (Maher & Lustig, s.a.; Crennan & Booth, 2007). But participants of a pilot project in Vanuatu did not see any problems regarding this fact (Crennan & Booth, 2007). In general, users prefer more convenient systems, so called 'flush-and-forget' or 'drop-and-forget' systems, such as flush toilets which are supposed to be the most desired option in Vanuatu (Rieck et al., 2012; Crennan & Booth, 2007). The success of this system depends on a full understanding of the concept held by the users (Brikke, 2000). Therefore, awareness raising, and proper training is very important for the sustainability of this system (Calvert, 2013). Depending on whether the end product is used as fertilizer or not, there can be constraints regarding the acceptance of using decomposed human waste as fertilizer, but it can be disposed of alternatively (Rieck et al., 2012). Best acceptance of this technology has been attained when there is an interest of the people in recovering the nutrients and saving water. Nevertheless, this type of sanitation is oftentimes perceived to be inferior in status, hygiene and comfort, especially in comparison to water-based systems (Werner et al., 2004).

III. FURTHER CONSTRAINTS & RISKS

Greywater and anal cleansing water have to be collected and treated separately. A storage tank for the urine is needed (Tilley et al., 2014). Further, the urine can be used as fertilizer after being stored for at least one month. When the users are too eager to use the product as fertilizer, they may apply it too early although it is not pathogen-free at this time (Brikke, 2000).

IV. FURTHER ADVANTAGES

This system can be used indefinitely, is suitable for rocky as well as densely populated areas and can be built with locally available materials. After a storage time of minimum 6 months (halved in comparison to 'Waterless Pit System without Sludge Production'), the dehydrated faeces can be excavated manually and is much easier to handle than sludge. If there are hygienic concerns, it can be further treated or simply disposed of. Urine and dehydrated faeces can be used as fertiliser respectively soil amendment as long as proper reuse practices are applied (Calvert, 2013; Tilley et al., 2014). The urine can be used immediately in case it is used on household level (WHO, 2006). Moreover, flies and odours are of almost no concern (Tilley et al., 2014). Rieck et al. (2012, p. 6) state that, *'[…] UDDT technology has recently gained attention as an adaptable sanitation solution for areas affected by climate change. UDDT technology addresses local water scarcity or flooding and may contribute to food security in areas with climate-induced migrations.'*

6.2.5 BIOGAS SYSTEM

OVERVIEW

- DESCRIPTION: Excreta (from humans and animals) is collected, stored and treated in a Biogas Reactor. The biogas, which is produced through anaerobic digestion, can be used as source of energy. Besides biogas, the reactor constantly discharges a digestate (Sludge).
- USER INTERFACE: Pour-Flush Toilet, Urine-Diverting Flush Toilet, Urinal
- INPUTS: Blackwater, brownwater, urine, organic waste, animal waste
- AREA OF APPLICATION: Rural & peri-urban areas (Tilley et al., 2014)

EVALUATION AGAINST CRITERIA

I. APPLICABILITY

a. High groundwater table

The reactors can be built above or below ground and are airtight (Tilley et al., 2014). *'Even though the biogas tank is gas- and watertight, it should not be constructed in areas with high groundwater tables or where there is frequent flooding, without any coating similar as a fresh water tank or a swimming pool'* (Mang & Li, 2009, p. 8).

b. Flood resilience

The biogas reactor can be constructed to withstand flood damages (Sherpa et al., 2014). Nevertheless Mang & Li (2010) do not recommend the system in areas with frequent flooding.

c. Water dependency

Considerable amounts of water are necessary for the dilution of faeces. Greywater can also be used for dilution. Nevertheless, too much greywater input reduces the hydraulic retention time significantly (Tilley et al., 2014; UNEP, 2002).

II. OPERATION & MAINTENANCE; USER ACCEPTANCE

a. Operation & Maintenance

Besides a constant supply with organic substrate, preferably animal manure and market/kitchen waste, an adequate sludge management is a crucial factor. This includes the use, storage and transport of the constantly produced digestate (preferably on-site). The continuously discharged sludge is not free from pathogens. Therefore, additional treatment may be necessary, depending on the intended reuse (Tilley et al., 2014). Every 5 to 10 years the reactor chamber must be desludged. This is usually done manually, hence no space is needed for vehicular access. (Vögeli et al., 2014).

b. User acceptance

UNEP (2002, p. 93) rates this technology as culturally accepted in the pacific region, but its application is still very rare. On the one hand the beneficiaries have an additional energy source. On the other hand, the risk and complexity of the system may hamper the acceptance (UNEP, 2002).

III. FURTHER CONSTRAINTS & RISKS

The generated biogas must be utilized continuously. Otherwise the pressure in the tank rises and the gas could leak through the outlet. An expert is needed for the design and construction of the system. Risks associated with flammable gases should be considered. Another disadvantage is given by the fact that the reactor has to be located close to the end-use, in order to minimize distribution losses (Tilley et al., 2014).

IV. FURTHER ADVANTAGES

Biogas can be used as energy source for cooking, lighting or electricity generation. The system needs little space, as most of its components can also be built underground. The system can be designed for household level as well as for small neighbourhoods. The generated sludge can be used as fertilizer for agricultural purposes. No electrical energy is required for the operation of the reactor (Tilley et al., 2014). According to Monvois et al. (2010) the lifespan of this system is between 25 to 50 years.

6.2.6 BLACKWATER TREATMENT SYSTEM WITH INFILTRATION

OVERVIEW

- DESCRIPTION: This water-based system requires proper storage and treatment facilities (septic tanks, Anaerobic Baffled Reactor, anaerobic filter), that are able to handle large amounts of waste water. The effluents are then infiltrated or evaporated, and the generated Sludge requires further treatment.
- USER INTERFACE: Pour-Flush Toilet, Cistern Flush Toilet
- INPUTS: Faeces, urine, flushwater, anal cleansing water, dry cleansing material
- AREA OF APPLICATION: Where sufficient space for infiltration technology & suitable soil properties are available (Tilley et al., 2014).

EVALUATION AGAINST CRITERIA:

I. APPLICABILITY

a. High groundwater table

Septic tanks, Anaerobic Baffled Reactor (ABR) and anaerobic filters, especially with infiltration, are generally not well qualified in areas with high groundwater table (ARGOSS, 2001; Tilley et al., 2014). Septic tanks are theoretically preferable to pit latrines regarding groundwater quality protection, given the tanks are constructed and maintained properly, which is often not accomplished (Falkland, 2002; Dillon, 1997). In areas with seasonal fluctuations of the water table exceeding 1.5m, a secondary treatment of the effluent is necessary (Gutterer et al., 2009). Falkland (2002) classifies septic tanks as inappropriate for small island countries and concludes that septic tanks are *'[…] definitely not appropriate in coral islands and many coastal areas of high islands'* (Falkland, 2002, p. 54).

b. Flood resilience

This system is not apt for areas prone to floods (Monvois et al., 2010; Tilley et al., 2014). The surrounding environment can be contaminated when treatment facilities are inundated, further the backflow of wastewater into the toilet facility may occur. A non-return valve can be installed to overcome this problem. Further the flooding of soak pits and leaching fields is of major concern (Sherpa et al., 2014).

c. Water dependency

This system relies on water and is therefore not suitable for all areas in Vanuatu (Brikke, 2000; Tilley et al., 2014; UNEP, 2002).

II. OPERATION & MAINTENANCE; USER ACCEPTANCE

a. Operation & maintenance

Tilley et al. (2014, p. 31) state, *'[t]his system is only appropriate in areas where desludging services are available and affordable and where there is an appropriate way to dispose of the Sludge'.* The system needs to be desludged (sludge and scum) every 2-5 years (septic tank) or 1-3 years (ABR) and the sludge must be treated subsequently. The emptying and transport of the sludge can be done human-powered or motorized, proper infrastructure like roads are advantageous but not mandatory (Tilley et al., 2014; Cruz et al., 2005). Besides that, there should be a regular check if the tanks are still watertight (Tilley et al., 2014). Although septic tanks and pit latrines are widespread in Vanuatu, emptying services are only provided in the capital (Port Vila, Efate) and are too expensive for most people. Furthermore, the country lacks a proper sludge treatment so far, the common procedure is the disposal of the sludge on a landfill without pre-treatment (Castalia, 2005). This disposal site overflows frequently into the adjacent Teouma River (Kassis, 2010). A new disposal site including treatment and the construction of a biogas plant for sludge treatment in form of a CDM (clean development mechanism) project was proposed (VPMU, 2013).
Emptying of septic tanks is often only done when malfunctions occur (e.g. bad odours or blockages of the in-house drainage system). Infrequent or no emptying of the tank results in short retention times of the wastewater and the effluent leaves the system without proper treatment. In the case the tanks are emptied, it is common practice in Pacific Island Countries to dispose of the sludge in a pit dug next to the tank or to dump it in a landfill without pre-treatment (Crennan & Berry, 2002). This may occur in Vanuatu as well, as *'[v]illage access is often difficult, with boats predominately used to service the 83 islands and many of the existing roads in poor condition or not extensive enough'* (Stitt, 2005, p. 2). Besides, there are no control mechanisms of the proper construction and maintenance of septic tanks (Government of Vanuatu, 2010).

b. User acceptance

User acceptance is good as flush toilets are supposed to be the most desired option in Vanuatu (Crennan & Booth, 2007; UNEP, 2002). According to Crennan & Booth (2007) the problems related to septic tanks and pit latrines in regard of groundwater and coastal areas are known among some communities in Vanuatu.

III. FURTHER CONSTRAINTS & RISKS

There is only a low reduction in pathogens, solids and organics (septic tank) and low reduction of pathogens and nutrients (ABR and anaerobic filter). Besides the aforementioned mandatory emptying and subsequent treatment of the sludge, the effluent has to be properly infiltrated. The infiltration is restricted in areas with high groundwater tables. ABR and anaerobic filter require an expert design and construction as well as a starting time of several months to reach its full treatment capacity (time can be decreased by adding fresh cow dung or septic tank sludge). The filter of the anaerobic filter must be cleaned regularly due to its proneness to clogging (Tilley et al., 2014). The effluent can cause major environmental and health risks, if it is not maintained properly (UNEP, 2002).

IV. FURTHER ADVANTAGES

Anal cleansing water and easily degradable dry cleansing material can be collected together with the excreta, additionally the combined treatment with greywater is possible. ABR and anaerobic filter have a high BOD removal and produce low volumes of stabilized sludge (Tilley et al., 2014).

6.2.7 BLACKWATER TREATMENT SYSTEM WITH EFFLUENT TRANSPORT

OVERVIEW

- DESCRIPTION: This system uses a household-level technology ('interceptor tanks' e.g. septic tank) to remove and digest settleable solids from the blackwater. Afterwards the effluent is discharged via a simplified or solids-free sewer system to a treatment facility. Additional effluent management is necessary.
- USER INTERFACE: Pour-Flush Toilet, Cistern Flush Toilet
- INPUTS: Faeces, urine, flushwater, anal cleansing water, dry cleansing materials, greywater
- AREA OF APPLICATION: Especially apt for urban areas (Tilley et al., 2014).

EVALUATION AGAINST CRITERIA

I. APPLICABILITY

a. High groundwater table

Both types of sewer (simplified and solids-free) are watertight and can be installed in shallow depths. The system is therefore suitable for regions featuring a high groundwater table, as long as the 'interceptor tanks' are watertight (Tilley et al., 2014). However, a very high groundwater table can have several drawbacks. Leakages in the pipes may contaminate the groundwater and groundwater permeating into the sewer network may result in a higher effluent volume discharged to the treatment facility. Furthermore, the construction of the sewer network will be more complicated under this condition (Monvois et al., 2010).

b. Flood resilience

Simplified and solids-free sewers are laid in a shallow soil depth, which makes them vulnerable to flood damages. Nevertheless, collection facilities can be designed to be applicable in flood prone areas. Furthermore, treatment facilities (e.g. waste stabilization ponds, aerated ponds, trickling filter) are at risk to overflow and being damaged. Protective measures like dykes can prevent treatment facilities from being flooded. Adaption of collection facilities like anchoring the sewer to the ground, sealing manholes or installing non-return valves may be necessary (Sherpa et al., 2014).

c. Water dependency

A piped water supply is required for both sewer types (UNEP, 2002). Monvois et al. (2010) state that in order to prevent clogging the local water supply must be at least 40 to 50L per person per day, depending on the gradient and diameter of the sewer.

II. OPERATION & MAINTENANCE; USER ACCEPTANCE

a. Operation & maintenance

The sludge generated in the 'interceptor tank' has to be treated in a dedicated facility. Further the effluent discharged via the sewer system requires a (semi-) centralized treatment. This combination of technologies is classified in pre-, primary-, secondary- and tertiary treatment (e.g. settler, Imhoff tank, ABR, anaerobic filter, WSP, aerated pond, constructed wetland, trickling filter, UASB and/or activated sludge). The emptying and transport can be done human-powered or motorized, proper infrastructure like roads are advantageous but not necessary (Tilley et al., 2014; Cruz et al., 2005). Furthermore the (semi-) centralized treatment facility also generates effluent and sludge, which demand further treatment. In comparison to conventional sewer systems, this system needs repairs and removals of blockages more often due to smaller pipe diameters (Tilley et al., 2014).

b. User acceptance

In general, users prefer so called 'flush-and-forget' systems, which are supposed to be the most desired option in Vanuatu (Rieck et al., 2012; Crennan & Booth, 2007). This system requires high user commitment, especially with regard to desludging the interceptors. One inadequately maintained tank could have negative implications for the whole sewer system (Tilley et al., 2014). UNEP (2002, 93) rates this technology as culturally accepted in the pacific region, but its application is still very rare.

III. FURTHER CONSTRAINTS & RISKS

The design, construction and supervision of the system must be undertaken by experts (Monvois et al., 2010; Tilley et al., 2014). The lack of electricity can cause operational failure of treatment systems (e.g. aerated ponds, trickling filters, UASBs, activated sludge) (Sherpa et al., 2014). The system requires high capital investment (Tilley et al., 2014).

IV. FURTHER ADVANTAGES

Simplified or solids-free sewer can be dug by hand. Further they are routed within property boundaries, resulting in shorter networks. The construction of these sewers is therefore cheaper compared to a conventional sewer system. This system can be used to upgrade existing on-site collection and storage/treatment technologies, which enhances the overall treatment performance. For example, if the effluents from septic tanks pollute the groundwater, then a sewer network can be installed to transport the effluents to a treatment facility (Tilley et al., 2014; UNEP, s.a.). Furthermore, the treated effluent may be used for irrigation, fish ponds or can simply be discharged to a receiving water. Another advantage is the combined discharge and treatment with greywater (Tilley et al., 2014).

6.2.8 BLACKWATER TRANSPORT TO (SEMI-) CENTRALIZED TREATMENT SYSTEM / OPTIONAL URINE-DIVERSION FLUSH TOILET

OVERVIEW

– DESCRIPTION: A sewer system is used to transport the Blackwater directly to a centralized or semi-centralized treatment station. The Sludge generated in these facilities requires further treatment. Optionally a separation of yellow- and brown water is possible by using a (UDFT).

- USER INTERFACE: Pour-Flush Toilet, Cistern Flush Toiler; Urine-Diverting Flush Toilet, Urinal
- INPUTS: Faeces, urine, flushwater, anal cleansing water, dry cleansing material, stormwater
- AREA OF APPLICATION: Especially suited for dense areas like urban or peri-urban settlements (Tilley et al., 2014).

EVALUATION AGAINST CRITERIA

I. APPLICABILITY

a. High groundwater table

The conveyance system (sewer) is applicable in areas with high groundwater table in general (assuming water tightness of the sewer). Nonetheless leakages are difficult to identify and pose a risk to groundwater contamination. Ground shifting and vibrations from earthquakes may cause cracks leading to leakages. The (semi-) centralized treatment technologies can be chosen and designed to be apt for high groundwater tables (Tilley et al., 2014).

b. Flood resilience

Combined sewers are not considered to be state of the art and adverse when flooding occurs, but conventional and simplified sewers without stormwater can be used, given that these are tight (Tilley et al., 2014). Simplified sewers are prone to be exposed and damaged by a flood due to their shallow depth. Nevertheless, collection facilities can be designed to be applicable in flood prone areas. Furthermore, treatment facilities are at risk to overflow (e.g. waste stabilization ponds, aerated ponds, trickling filter) and being damaged. Protective measures like dykes can prevent treatment facilities from being flooded. Adaption of the collection facilities like anchoring the sewer to the ground, sealing manholes and/or installing non-return valves can be necessary. Sherpa et al. (2014) state that, the semi-centralized approach is considered to be the least suitable option for flood situations.

c. Water dependency

This system relies on a constant water supply and is therefore not suitable for all areas in Vanuatu (Tilley et al., 2014). Conventional sewers require a piped water supply of minimum 50L per day, simplified need between 40 and 50L per day (Monvois et al., 2010).

II. OPERATION & MAINTENANCE; USER ACCEPTANCE

a. Operation & maintenance

The operation and maintenance of the sewer system is elaborate and requires skilled personnel. Especially on atolls and in coastal areas pumps are often needed for conveyance, which rely on electricity and must be maintained (UNEP, 2002). Simplified sewers require removals of blockages and repairs more often than conventional ones and need well trained as well as responsible users for maintenance. Conventional sewers should only be maintained by professionals and can produce dangerous toxic gases. The semi-centralized and centralized treatment facilities are designed for large user groups and the operation, maintenance and energy requirements are higher than in case of on-site facilities in general. A range of semi-centralized treatment facilities is available (e.g. wetlands, anaerobic filters, drying beds). The operation and maintenance of the various treatment facilities is not included in this analysis. If a UDFT is used, the urine storage tank has to be emptied and cleaned regularly (Tilley et al., 2014).

b. User acceptance

User prefer convenient, so called 'flush-and-forget' systems (Rieck et al., 2012). Flush toilets are supposed to be the most desired sanitation option in Vanuatu (Crennan &

Booth, 2007). If UDFT's are used, the user needs proper training and the acceptance may be lower compared to a standard cistern flush toilet (Tilley et al., 2014).

III. FURTHER CONSTRAINTS & RISKS

This system is not suitable for low population densities. Sophisticated conveyance and treatment results in high capital costs. This leads to high debt loads for small communities (Tilley et al., 2014; Zhang et al., 2014). A combined sewer system discharges the wastewater together with stormwater and can lead to very high flow rates in treatment plants as well as combined sewer overflows, resulting in environmental and health hazards (Cruz et al., 2005). According to Tilley et al. (2014, p. 35) '*[t]his system is most appropriate when there is a high willingness and ability to pay for the capital investment and maintenance costs and where there is a pre-existing treatment facility that has the capacity to accept additional flow*'. Sewers must be designed and constructed by experts. Conventional sewers require deep excavations which are very laborious by hand and additional connections are elaborate (Tilley et al., 2014). The lack of electricity can cause operational failure of treatment systems (Sherpa et al., 2014). In the case of UDFT's, the availability of the user interface is limited. Usually they cannot be built or repaired locally. Additionally, the interface is prone to misuse and clogging (Tilley et al., 2014).

IV. FURTHER ADVANTAGES

Anal cleansing water, dry cleansing materials, greywater and possibly stormwater, in case of conventional sewers, can be discharged together to the (semi-) centralized treatment facility. Discharging greywater is preventive against clogging and accumulations. Simplified sewers are cheaper than conventional sewers, because they require a shallower depth and lower gradient. They can be dug by hand and can be extended when the community grows. Further they are routed within property boundaries, resulting in shorter networks. Conventional sewers can deal with high volumes of flow (Tilley et al., 2014). In case a UDFT is used, the stored urine can be applied as fertilizer for agricultural purposes due to the high nutrient content (Tilley et al., 2014).

6.3 SUMMARY AND SYSTEM SELECTION

In the following a concluding selection of the analysed sanitation systems is provided. Each system was assessed in regard of their applicability under the prevalent conditions. In the beginning of this chapter the requirements, a system must fulfil, were presented. These are:

- Prevention of groundwater contamination
- Operability and safe containment of excreta during and after flood events
- No or low water demand

Systems that do not fulfil all requirements are excluded. In combination with the other three criteria (operation & maintenance, user acceptance; further constraints & risks; further advantages), one system was identified to be best applicable under the present conditions.

The SINGLE PIT SYSTEM seems to be not well suitable for these specific conditions. A potential groundwater contamination, due to pathogen infiltration is likely, especially if the pits are dug until the water table is reached. The risk of overflowing pits resulting in pathogens being spread in the environment, makes this system unsuitable for flood prone areas.

In the case of the WATERLESS PIT SYSTEM WITHOUT SLUDGE PRODUCTION, the vaults of the Double VIP and Fossa Alterna latrines are not sealed in order to infiltrate the liquids into the surrounding soil. Considering a high water table these systems can lead to a contamination of the groundwater resources. In regard of floods, these pit-based options are unsuitable, like the Single Pit system. Composting chambers are excluded due to its sophisticated design and operation, which is not suitable in this context. The Double Vault Composting Toilet would fulfil the main requirements, as the watertight vaults are built above ground. But the system requires high user dedication and know-how in order to attain conditions inside the vaults, that enable composting treatment. Hence it is excluded from subsequent planning steps.

The POUR FLUSH PIT SYSTEM WITHOUT SLUDGE PRODUCTION is not suitable to be applied under these conditions. It is based on the assumption of pits being permeable that liquids can be infiltrated into the ground. In the case of a shallow groundwater table this system has a high contamination potential. Further the unsealed pit is inappropriate for flood prone areas. If additional water enters the pit, the dewatering process will be impaired.

THE WATERLESS SYSTEM WITH URINE DIVERSION seems to be well suitable under the prevalent conditions. The fact that the vaults are sealed and built above ground allows the implementation in areas with a high groundwater table as well as in flood-prone areas. Furthermore, no water is required for the operation. Several case studies showed the feasibility of this system under these specific circumstances. Hence the UDDT systems was chosen for the subsequent design and cost considerations.

Due to its complexity and risks, which even increase under the prevalent conditions, the BIOGAS SYSTEM it is not included in the further analysis.

The BLACKWATER TREATMENT SYSTEM WITH INFILTRATION is not applicable under the prevalent conditions. Infiltration in areas with a high water table can contaminate the groundwater resources. Flooding of the treatment facilities can result in similar adverse effects, by contaminating surface and groundwater bodies.

The BLACKWATER TREATMENT SYSTEM WITH EFFLUENT TRANSPORT could be implemented, if on the one hand an adequate operation and maintenance concept is applied. On the other hand, an appropriate facility for sludge treatment must be in place, which is not the case in Vanuatu.

For several reasons THE BLACKWATER TRANSPORT TO (SEMI-) CENTRALIZED TREATMENT SYSTEM / OPTIONAL UDFT is not included in the further analysis. The complexity of the system requires expert knowledge for the construction as well as the operation and maintenance. It is not appropriate for rural areas with a low population density. Especially in small communities the implementation of this system would result in high costs.

7. DESIGN ASPECTS OF THE URINE-DIVERTING-DRY-TOILET SYSTEM

7.1 OVERVIEW

An adequate design and construction are the basis of every well-performing sanitation system. Over the years the designs of on-site sanitation technologies evolve, as experience and findings gained in the field, are incorporated. The following chapter gives detailed recommendations for the design and construction of UDDTs. These literature-based guidelines are complemented with findings from the on-site research in Vanuatu. The focus is on aspects related to technical planning and design of UDDTs. Thus, other crucial elements like operation and maintenance or awareness raising concepts are not included.

Since the late 1990s UDDTs have been seen as feasible alternative to Pit Latrines and Flush Toilets. Basically, the concept of the UDDT follows three functional design elements: separation of urine and faeces at the source, waterless operation, and faeces storage and treatment in ventilated chambers. The source separation of urine and faeces is achieved by specific user interfaces. Urine is stored in tanks or containers or disposed of alternatively. After a certain storage period the urine can be applied as fertilizer on agricultural fields. As the name UDDT suggests, this system is operated without flushwater. After defecation the user covers the fresh faeces with a dry cover material to absorb moisture, limit odours and inhibit insect infestation. Regarding the faecal collection and storage mechanism it can be distinguished between UDDTs with single or double dehydration vaults. Some UDDT designs use interchangeable containers. In the following only UDDTs with double dehydration vaults, which are used alternatingly, are considered. When the first vault is full, it is closed, and the second vault is put into service. The treatment of the faecal content inside the vault is based on desiccation. Most of the moisture content in the faeces evaporates and is exhausted via the ventilation system or is absorbed by the previously applied dry cover material. This process substantially reduces the pathogen load of the pit content, making it safe to handle after a certain amount of storage time. After the storage period, the dried, odourless faecal content is removed from the vault and is either disposed of in a burial pit or used as agricultural soil conditioner. Then the cycle starts again, as the second vault is closed and allowed to rest while the first one is getting filled up (Rieck et al., 2012).

7.2 DEHYDRATION VAULTS

7.2.1 GENERAL DESIGN ASPECTS

Dehydration vaults fulfil two main purposes: First, they should safely collect and store the faecal matter. It is important that the vaults prevent any human contact with faeces, except from periodical emptying and cleaning. Second, the vaults should assure dry conditions in order to enable the content to desiccate and stay dry and odourless. Therefore, they are usually built above ground to avoid rain and floodwater from getting into the chamber. When choosing the location of the UDDT the topography of the area must be considered. It should not be built in a depression, as the vaults may be flooded during rainfall events (Rieck et al., 2012; WECF, 2015). In floodprone or waterlogged areas a raised plinth, which elevates the base plate at least 10cm above ground level, should be built (Calvert, 2013; Rieck et al., 2012). A vault floor, which is elevated above ground level, also facilitates emptying and cleaning of the chambers. To sustain safe containment and effective treatment of the faecal matter, several principles for the design of the vaults should be considered. Depending on the local ground conditions, the construction of a foundation may be required. A concrete foundation with a depth of 30 cm and a width of 25 cm is suitable for most grounds. To safe cement and costs, it is possible to first put stones in the excavation and then fill the remaining gaps with concrete (see Figure 6) (WECF, 2015). The physical structure of the vaults, especially the foundation and the outside walls, must be robust and stable to carry the weight of the users and the superstructure. Various materials, like bricks (see Figure 6), cement slabs, cement blocks, chiselled natural stone or adobe bricks, can be used for the construction of the walls (Rieck et al., 2012; WECF, 2015; Crennan, 2007). To avoid water from entering the vault, Tilley et al. (2014) recommend using sealed brickwork or concrete. Calvert (2013) advises to line the walls of the chambers with cement. This eliminates the risk of water trickling through the walls and facilitates easier and cleaner emptying. A layer of wire mesh can be used to make the cement stick properly to the inside walls (Hoffmann, 2012). The ceiling of the faeces chamber (i.e. slab) can be built from wood or concrete. If wood is used, it must be sealed with waterproof materials to prevent wetting the wood during cleaning (WECF, 2015). Concrete slabs should be reinforced with a steel mesh or iron rods (Hoffmann, 2012). In any case the slab should be covered with materials that allow easy cleaning like tiles or linoleum (WECF, 2015). The utilisation of locally available materials can result in a significant reduction of construction costs (see chapter 9.2.4) (Rieck et al., 2012). The holes for the urine pipes can be connected through the side walls and should be at least 50mm wide. A dividing wall separates the two vaults. On the back wall, openings for the vault access doors must be left out (WECF, 2015). To achieve ideal ventilation the vaults and access doors must be air-tight (see chapter 7.3) (Drangert, 2010). The floor of the faeces chamber should be at least 7-10cm thick and made out of high-quality concrete. Further it should be levelled and a slight slope of 1-2% towards the chamber doors helps to drain water or urine, that inadvertently entered the vaults (WECF, 2015). A smooth, durable floor surface, constructed out of tiles or polished concrete, enables easy cleaning of the chambers (Rieck et al., 2012).

Figure 6: Stone-filled excavation for foundation (left) (WECF, 2015, p. 26, adapted), Vault construction with bricks (right) (Rieck et al., 2012, p. 17, adapted).

7.2.2 DIMENSIONING OF THE DEHYDRATION VAULTS

The required storage volume respectively the dimensioning of the two dehydration vaults depends on two factors: the total volume of faecal material and the necessary storage time. The volume of faeces is determined by the *'number of users, their diet, the frequency of toilet use and the covering and wiping material used'* (Rieck et al., 2012, p. 17). The median wet mass of excreted faecal material is 250g per person per day in low income countries, which accounts for 38g/cap/day faecal dry mass. This value is mainly determined by body weight, total food intake and diet. Faecal wet mass is positively correlated with fibre intake. Hence a high fibre, vegetarian diet results in more faecal wet mass compared to a diet which is high in protein. Moreover, non-degradable fibre has a high water holding capacity which leads to a higher water content of the faecal material of a vegetarian diet (78.9%) compared to a diet with more protein (72.6%) (Rose et al., 2015; Geurts, 2005).

The storage duration has a critical impact on the treatment process. Most pathogens, except helminth eggs, die-off over time, once they are outside the human body. *'After defecation, the faecal pathogen load is naturally reduced through antagonism, competition and consumption by other microorganisms, as well as by the action of antibiotics'* (Niwagaba, 2009 cited in Rieck et al., 2012, p. 15). Exact predictions of storage durations cannot be made, since conditions vary for each situation and die-off rates are different depending on the type of microorganism (Schönning

& Stenström, 2004). Yet the WHO (2006) propagates recommendations for storage durations of dry excreta based on different ambient temperatures and alkalinity of the stored material. If ash or lime are used as cover material, which results in alkaline treatment (i.e. increase in pH-value), then a storage time of at least six months inside the dehydration vaults is recommended. Without alkaline treatment the storage duration should be extend to 1 year in warm climates respectively 1.5 to 2 years in colder climates (Tilley et al., 2014). In the case of Vanuatu (average temperature between 23.5 and 27.5°C) a minimum storage duration of more than one year is required (WHO, 2006a; Australian Bureau of Meteorology & CSIRO, 2011a). *'In general, longer storage periods deliver an end product with a lower pathogen and moisture content'* (Rieck et al., 2012, p. 16).

To guarantee a sufficient storage time inside the vault, it must be designed large enough for the expected number of users. Rieck et al. (2012, p.17) state that *'for design purposes, it can be assumed that the average person will require approximately 50 litres of faecal matter storage space for a 6-month period'.* Typically, dehydration vaults are designed with a volume of 500L for each chamber (Rieck et al., 2012). For the dimensioning of the vaults it should also be considered that the faeces are not evenly distributed in the chamber (i.e. formation of a conical pile), a proper airflow is ensured, a buffer zone between the faecal pile and the bottom of the slab is in place and that visitors may also use the toilet. This can be taken into account by increasing the required storage volume by 20% (Rieck et al., 2012; Tilley et al., 2014). Moreover, the disposal of wiping material must be considered in the dimensioning of the vaults. Tilley et al. (2014) recommend to not throw dry cleansing material like toilet paper into the chambers. The material will take up space in the chamber, which decreases its operational time. Further the wiping material will not decompose during the storage time, which is especially unfavourable if the vaults content should be directly applied onto agricultural fields. If no further treatment is planned, then the material should be collected separately in a bin and disposed of subsequently. On the contrary, Rieck et al. (2012) recommend throwing soiled wiping material like toilet paper, newspaper or leaves into the dehydration vaults. Materials, contaminated with faecal pathogens, should not be collected separately but rather stored safely inside the chambers. Moreover, wiping material can enhance the dehydration of faeces, by absorbing moisture inside the vaults (Rieck et al., 2012).

The outside walls of the faeces vault should have a minimum height of 60 to 80cm. This allows easy emptying of the vaults and access to the urine pipes in case of maintenance requirements (WECF, 2015; Tilley et al., 2014). A higher vault enables a longer operation and storage time, but adversely a higher stair is required, which can make access for elderly or small children more difficult (Hoffmann, 2012). Further a bigger vault increases the material costs for construction. Chapter 8.2 provides an estimation of the required vault volume for the pilot site on Emae.

7.2.3 Dehydration vault doors

The faeces vault doors should seal the access hole properly, to prevent water from entering, minimize the risk of human contact and provide darkness in the chamber, so that faeces are not visible for the users. Due to the fact that access doors are a common source of error, like poor design and construction or material defect, special care should be taken in this regard (Rieck et al., 2012). Inspections of several Composting Toilets in Vanuatu confirmed this problem. Although Composting toilets work with different treatment process than UDDTs, the vaults and requirements for the vault doors are basically the same. Almost all Composting Toilets visited during the on-site research showed deficiencies regarding the vault access doors (see Figure 7). These malfunctions can primarily be ascribed to poor design, unsuitable materials, improper implementation or insufficient maintenance. By following several guidelines, the risk of failure can be reduced. The doors should lock the access holes firmly by using rails, hooks, locks, hinges or a temporary concrete seal to prevent unintended opening. Further they should avert rainwater from entering the vault. Hence it is advisable to protect the doors with a roof overhang, at best sloping away from the access doors. The use of vertical rather than inclined access doors makes them less susceptible to rainwater intrusion (Rieck et al., 2012).

Figure 7: Defect vault doors of Composting Toilets in Vanuatu.

Austin (2006) recommends orienting the toilet in a way, that the ground slopes away from the access doors, in order to drain stormwater away from the vault access. Vault doors should be made out of robust, weather resistant materials like galvanised or painted steel, treated wood, concrete, bricks and mortar or plastic plates (Rieck et al., 2012). It is advisable to regularly paint the vault doors with waterproof material (e.g. tar) (Hoffmann, 2012). If plastic vault doors are used, they should not be transparent, since they also act as a visual barrier for the people walking by (Rieck et al., 2012). Plastic covers, which are exposed to sunlight can deform and start to bend, decreasing the tightness of the access hole. This may be alleviated by using thicker, more robust plastic covers (Ali, 2012). Using metal doors (e.g. iron, aluminium) compared to wood doors, prevents damages from rodents, like mice or rats (WECF, 2015). However, Ali (2012) reports problems with metal covers due to corrosion. Corroded covers may not close correctly resulting in problems with water intrusion, vectors and odours. Delepiere (2011) also mentions problems with corroded galvanised steel doors of UDDTs in flood-prone areas of Bangladesh, which led to rainwater infiltration into the faeces chambers. In this case the steel sheets corroded already after two years and were then replaced with concrete doors (see Figure 8). In any case, the material used for the covers should allow easy maintenance, like cleaning or applying rust-proofing paint. The vault access can also be closed with semi-permanent doors made of brick, stone, adobe, concrete or wood (see Figure 8). These doors are temporarily sealed with materials like weak mortar, clay, soil or nails. When the vault must be emptied the sealing is carefully broken and removed. After the emptying the same materials can be used to reseal the vault. Semi-permanent options can be beneficial if the doors are exposed to the public and are prone to vandalism. Nevertheless, they should only be used if a constant supply with sealant material is ensured and if the people in charge are trained to reinstall the doors properly (Rieck et al., 2012). A door size of 60x60cm or bigger allows entering the chambers, in case of necessary repair works (WECF, 2015). To avoid odours inside the toilet cubicle a constant airflow from the cabin through the chambers into the ventilation pipes is crucial. Reducing the airflow through the access doors is an important factor in this regard (Rieck et al., 2012).

Figure 8: Semi-permanent vault doors made of concrete with metal handles (left) (Delepiere, 2011, p. 4, adapted); Semi-permanent brick and mortar vault doors (centre) (Rieck et al., 2012, p. 19, adapted); Rubber-sealed vault door to promote air-tight conditions (right) (WECF, 2015, p. 29, adapted).

By closing the gap between the door and the wall with a rubber seal the airtightness of the chamber and therefore the ventilation gets improved (see Figure 8) (WECF, 2015). In general, two different design options are possible for the access doors. They can either be built inclined or straight (see Figure 9).

Figure 9: Straight vault doors of UDDT (left) (GTZ Ecosan, 2019, adapted; inclined vault doors of UDDT (right) Winberg & Otterpohl (2016, p.1227, adapted).

The idea behind inclined doors is, that they should absorb as much solar radiation as possible ('solar latrines'). This is supposed to heat up the chamber, in order to increase pathogen die-off through higher temperatures and to speed up the desiccation process through improved ventilation. However, a study by Windberg & Otterpohl (2016) has shown that the commonly used and promoted design of solar latrines with inclined doors does not necessarily meet these expectations. '*The achieved temperatures are not high enough or held long enough to significantly increase the rate of dehydration or to even facilitate any hygienisation effect'* (Windberg & Otterpohl, 2016, p. 1242). Instead solar heated UDDTs often generate the following problems: The design with tilted chambers makes the construction more complicated and expensive. Inclined doors are more exposed to the weather. Hence metal sheets may corrode faster (see Figure 10). In fact, inclined vault doors are generally more susceptible to failure or vandalism than straight ones. Holes or gaps in inclined doors are more exposed to rainfall than vertical doors. Moreover, positioning the toilet in the suns path is often difficult to achieve. In practice shadows from bushes or trees often inhibit the desired insolation. Practical experience has shown that other factors, like user preferences for the toilet location, are more critical than orienting the chamber towards the sun. Hence, it is strongly recommended to always construct vertical access doors and stop promoting solar UDDTs as a standard solution (Windberg & Otterpohl, 2016; Rieck et al., 2012).

Figure 10: Corroded iron sheets of solar UDDTs (Windberg & Otterpohl, 2016, p. 1266, adapted).

7.3 VENTILATION

Basically, the prevention of odours in the faeces chamber of a UDDT depends mostly on proper operation. If the vault is kept as dry as possible, through urine diversion (UD) and the addition of moisture absorbing agents after defecation, then odours are often eliminated completely. Especially in hot and temperate climates, where desiccation of faecal material is accelerated, flies and odours should not be a problem, provided that the toilet is operated correctly (Austin, 2006). Nevertheless, even in very arid climates, UDDTs should always be equipped with a ventilation system as it ensures the desiccation of the faecal content and the elimination of odours. For outdoor toilets, with an airy superstructure, natural ventilation without any mechanical devices, is usually enough. This is achieved by a ventilation pipe that exhausts odours and moisture from the toilet chamber to an area, not less than 50cm, above the roof of the superstructure (Rieck et al., 2012). Natural ventilation occurs due to different air pressures inside and outside the toilet. The main drivers of this process are thermal differences and wind accumulation (Groth, 2005). A difference in temperature between the chamber and the ambient air, creates suction drawing fresh, cool air into the superstructure, onward through the drop hole into the chamber and finally releasing the warmer, waste air through the ventilation pipe into the environment (stack effect) (see Figure 11). Openings above the entrance door, along the walls or between the roof and the walls are usually enough to provide an adequate supply with fresh air (Rieck et al., 2012).

Figure 11: Air flow of natural ventilation system of a UDDT (left) (WiSDOM, 2016, p. 16, adapted); Construction of double dehydration vaults, each equipped with proper ventilation pipes (right) (Rieck et al., 2012, p. 17, adapted).

Austin (2006) states that ventilation takes place mainly due to winds blowing across the top of the vent pipe. This creates a draft into the drop hole onwards into the ventilation pipe, extracting the waste air from inside the chamber and the cubicle (vaults and cover doors should be airtight to not impede this process) (Drangert, 2010). Hence the outer rim of the hole in the cover slab, which allows connecting the vent pipe to the chamber, should be sealed properly (Austin, 2006). By extending the ventilation pipe at least 0.5m above the roof it is more likely to catch winds and thermal differences (Drangert, 2010). Caution is necessary in areas with very strong winds, as they can reverse the desired air flow and push the waste air down the vent pipe into the chamber (Groth, 2005). Under such conditions the toilet should be oriented in a way that the vault doors do not face the predominant wind direction (Rieck et al., 2012). If the entrance door faces the wind direction, then air will be pushed through the system in the desired direction (Morgan, 2009).

Ventilation pipes can be made out of several different materials, like polyvinyl chloride (PVC), asbestos or tin, whereas smooth walled PVC or asbestos tubes are most efficient. There is also the possibility of using homemade ventilation pipes. These are usually made of natural or recycled materials, like reed, plastic bottles, wire rings or newsprint paper, in combination with cement slurry or cement paint (Morgan, 2009). To achieve proper ventilation, friction inside the pipes must be minimized, hence they should ideally be straight without any bends. If corners are inevitable, it is advantageous to mount two 45° bends rather than one 90° angle (see Figure 12).

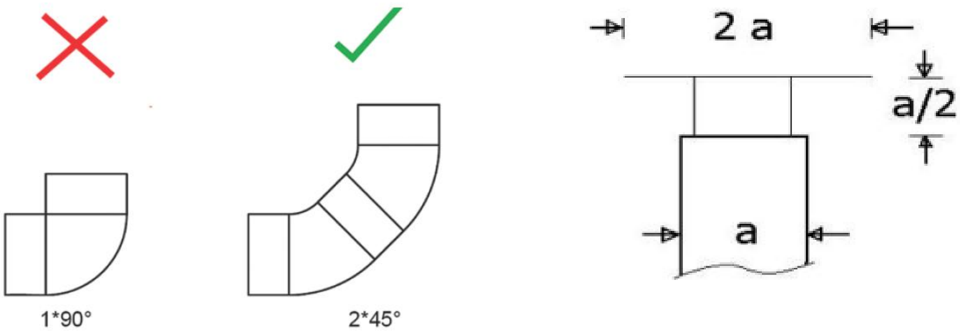

Figure 12: Incorrect and correct ways to install pipe bends (left) (WECF, 2015, p.37); adequate distance of vent pipe cover (right) (Groth, 2005, p. 66).

The diameter of the pipes should be at least 110mm (WECF, 2015). In very humid climates the diameter can be extended up to 250mm (Winblad & Simpson-Hebert, 2004). Whereas Drangert (2010) recommends dimensioning the pipes not larger than 150mm for optimal natural air flow. To prevent rain from entering the chamber the upper end of the pipe must be fitted with a T-joint or a rain-cap (see Figure 11) (WECF, 2015). Additionally, a vent pipe cover can enhance the air stream, which improves the draft into the vent pipe. As shown in Figure 12 the distance between the top end of the pipe and the cover must be wide enough to not decrease the air-flow rate (Groth, 2005). Although flies are usually not a problem in a well-operated UDDT, a corrosion resistant fly-screen should be installed on the upper end of the pipe (Austin, 2006). Morgan (2009) recommends aluminium screens as long lasting and relatively cheap option. It is possible to ventilate both chambers with one ventilation pipe and a connection hole in the dividing wall. Nevertheless Rieck et al. (2012) recommend installing one ventilation pipe for each vault. Moreover, the pipes can either be mounted inside or outside the toilet superstructure. Outside installation can have the advantage of an increased stack effect as the solar radiation increases the temperature in the pipe. However, pipes installed on the outside walls are vulnerable to accidental damage or vandalism and can become brittle due to UV radiation. Hence, they should be solidly mounted and coated with UV resistant paint (Rieck et al., 2012). In case the pipe is fitted through the roof it must be sealed in with silicone or other materials (WECF, 2015).

Ventilation pipes were another obvious weakness of the inspected Composting Toilets in Vanuatu (see Figure 13). Most of them showed several shortcomings in the design. None of the Composting Toilets was equipped with a separate ventilation pipe for each vault. Instead, both vaults were connected to the same pipe, by installing several 90° bends, resulting in decreased airflow due to more friction. Most ventilation pipes had a diameter of less than 100mm, which might be insufficient to cope with high humidity during the rainy season. Some of the pipes were

Figure 13: Examples of poorly designed ventilation pipes of Composting Toilets in Vanuatu (left & right: Only one pipe with 90° corners for both vaults; centre: Ventilation pipe with 90° corner does not extend above the roof of the superstructure).

not extended above the roof of the superstructure, thus inhibiting the stack effect and preventing drafts from winds blowing across the pipe. None of the pipes were covered with a rain protection at the top, and only some had a provisional fly-screen.

7.4 Superstructure

A separate superstructure must be built unless the toilet is constructed inside an existing house. The superstructures' main purpose is to provide privacy and comfort for the users. This can be accomplished by considering the following design principles. In contrast to other low-cost on-site sanitation systems, like the VIP toilet, the cubicle of a UD toilet should be airy and well lit. Thereby the attractiveness of the toilet is increased, and proper ventilation is possible. Enough windows or openings along the walls or above the door should provide proper lighting and ventilation. To ensure privacy for the user, ventilation gaps or windows should be installed above the height of a tall person. At night, artificial illumination should be provided (e.g. solar lights, emergency LEDs) (Rieck et al., 2012; Austin, 2006). The toilet floor should be made out of smooth and durable materials (like tiles or polished concrete), in order to allow easy and effective cleaning and have an attractive visual appearance. By slightly sloping the floor, cleaning water gets channelled towards a floor drain or another outlet. While sitting or squatting on the toilet the user should face the door or a side wall. Moreover, they should be able to move freely inside the cabin. Therefore, the minimum demand for space, of 90x120cm, must be anticipated. A study about acceptance of UDDTs in eThekwini municipality (South Africa) reports that, *'[i]nferior or incorrect design and construction of the UDDT was highlighted as a barrier to acceptance'* (Mkhize et al., 2017, p. 117). In this case the users felt that the UDDTs were inconvenient, since the space inside the superstructure was too limited. Further, the distance between the toilet seat and the walls or doors must be wide enough, at least 30cm, to avoid unintended body contact. Constructing the stairs outside the superstructure and installing outward opening doors is beneficial for having enough space inside the cubicle (Rieck et al., 2012). On the inside the door should be equipped with a sliding bolt or similar. Having the option to secure the door with a padlock from the outside, might be useful (Crennan, 2007). The design of the superstructure plays an important role concerning the acceptability of the latrine. It should be in accordance with the user's income and customs (SOPAC, 1997). In general, a wide variety of different materials can be used for the construction of the superstructure (see Figure 14). Criteria like strength, weather resistance, durability and thermal properties (heat conduction) should be considered when selecting the material. Hence using galvanised corrugated iron sheets is not recommended for the walls of the superstructure. Heat gain in the cubicle would diminish the user's comfort and should therefore be avoided (Austin, 2006). Unless the functionality of the system is not impaired, the design and materials can be adapted to comply with local practicalities and aesthetics. For example, the frame of the superstructure can be cladded with natural materials like pandanus thatch. It must be considered that the frame of the superstructure should be stable enough to withstand storm events. Particularly if the facility is located in a cyclone prone area, which is the case in Vanuatu. Following the traditional architectural style and using local materials can enhance the user's acceptability and will reduce the construction costs, as shown in chapter 9.2.4 (Crennan, 2007). With respect to the main requirements for the roof - being waterproof to keep rainwater out of the

Figure 14: UDDTs made from various building materials (GTZ Ecosan, 2019, adapted).

vault and being properly fixed to the side walls - several material options are feasible. These include tiles, shingles, ferrocement, precast concrete and galvanised corrugated iron. Roofs made of ferrocement or precast concrete are usually the most durable and need little maintenance. These construction types do not require timber beams or wire fixings (Austin, 2006). Beside these permanent materials the roof can also be thatched with local materials (Crennan, 2007). In any case the roof should overlap the structure on each side to avoid rainwater running down the walls (Deegener et al., 2006). If the superstructure is covered with a corrugated metal roof, then it can be used to collect rainwater for handwashing or cleaning, which is especially reasonable if other water sources are limited. The water can then be stored in a drum (e.g. 200 litres), with a tab fixed at the base (SOPAC, 1997). Rainwater harvesting has a long history in Pacific island countries (SOPAC, 2004). In fact, it is often the main source of drinking water for rural households in Vanuatu (VNSO, 2014). Hence the knowledge and resources for the construction of rainwater harvesting systems are already available in most communities.

EXCURSUS: SIMPLE HANDWASHING DEVICES

The SDG 6.2 (Sustainable Development Goal) is divided into two parts, dealing with access to adequate and equitable sanitation and hygiene for all. In contrast to the previous global targets (MDGs) hygiene and handwashing was included and takes a central role. *'Handwashing with soap and water is a top priority for improving global health and is one of the most cost-effective public health interventions. Good hygiene practices, such as handwashing with soap and water after using the toilet and before preparing food, are essential to prevent illness and limit the spread of communicable diseases'* (UN, 2018, p. 43). The priority indicator measuring hygiene under the SDGs, determines the proportion of the population with basic handwashing facilities on their premises. A basic facility is characterized by the on-site availability of soap and water. Facilities not only include sinks with tap water but also other appliances that contain, transport or regulate water flow, like portable basins, tippy-taps or buckets with taps (WHO & Unicef, 2017). Every toilet system should be equipped with a functioning hand washing facility. Many of these hand washing devices can be made easily with simple materials, which are available virtually everywhere. Morgan (2011) describes several techniques for building hand washers to almost no costs with recycled materials like alloy cans or plastic bottles.

One popular hand washing device is the so called Tippy-Tap. This low-cost device can be built rather simple with locally available materials. It is made up of a plastic jerry can (3 to 5L) with a small hole in the side wall. The filled jerry can is suspended on a wooden frame (see Figure 15). A string is mounted to the canister and connected to a piece of wood on the floor. When the wood is pressed down with the foot, it tips the jerry can and water flows out of the hole. A piece of soap can be tied up on a string next to it. A gravel or stone filled hole in the ground below the jerry can allows water to soak away without forming a puddle. A crucial advantage of the tippy-tap is that due the foot pedal there is no need to touch the device, which prevents a potential contamination and disease transmission. Moreover, the consumption of water is low, as only small amounts are released through the hole. A reported drawback is that parts of the tippy-tap have to be replaced regularly as they wear out and degrade due to UV radiation (Biran, 2011).

Figure 15: Tippy-Taps (left: Bopoma Villages, 2019; centre: Biran 2011, p.3; right: Milholland, 2019).

7.5 User Interface

7.5.1 General Design Aspects

The purpose of a urine diversion toilet is to separate urine and faeces at the point of source inside the toilet. This is accomplished by a simple system with two separate outlets, one for the urine and one for the faeces. The urine gets collected in a bowl located in the front section of the user interface. From there it is drained through the piping system into the storage tank or is disposed of via infiltration into the ground. The faeces drop directly through a hole in the back of the interface into the collection chamber. A dividing wall in the middle enables the separate collection of urine and faeces (Münch & Winker, 2011). A proper separation of the two sections is crucial in order to avoid urine splashing into the dry faeces chamber and to prevent faeces from falling into and clogging the urine bowl (Tilley et al., 2014). This faecal cross-contamination of urine can have significant health hazards if the urine is used as fertilizer for crop production (Stenström, 2011). The handling and reuse of urine, which is contaminated with faecal pathogens can lead to transmission of diseases (Rieck et al., 2012). Depending on the usage of flush water it can be distinguished between Urine-Diverting-Dry-Toilets, which operate without water, and Urine-Diverting-Flush-Toilets. Urine diversion toilets can either be designed as sitting toilets with a pedestal (wall-hung or installed on the floor) or as sitting toilets with benches with inserts or as squatting toilets with a squatting pan (see Figure 16) (Münch & Winker, 2011).

Figure 16: Scheme of different types of UDDT user interfaces (Tilley et al., 2014, p. 46).

Urine-diverting squatting pans are basically available in two different versions, a single drop hole and a twin drop hole version. The former one is equipped with a small hole for urine and a larger one for the faeces. In case of double vault UDDTs it is possible to either have one pan for each vault or a mobile pan that is placed above the active vault. The twin drop hole version is designed differently, with one hole for urine in the middle and one faeces hole at each end of the pan. Thus, only one pan, which can be mounted firmly to the floor, is needed for both vaults. Another difference to the single drop hole version is, that while squatting on the pan the user faces the side walls and not the door.

As shown in Figure 16, squatting pans can be adapted with a third drain for people who wash their anus after defecation (washers). Alternatively, a separate anal wash basin can be installed (Rieck et al., 2012). Within this thesis only Urine-Diverting-Toilets for sitting (urine-diverting seats) are considered, as sitting is the common posture in Vanuatu. Further anal washing is not included as people in Vanuatu usually wipe their anus after defecation (wipers). Regarding Urine-diverting toilets for sitting, two options are available. They can either be built as pedestals or as benches with inserts. For both options a sitting height of 38 to 45cm is recommended. Usually urine diversion pedestals make use of a divided toilet bowl that allows the separation of urine and faeces (see Figure 17). An alternative design was developed in South Africa and Namibia (see Figure 17, right) (Rieck et al., 2012). In this case *'[t]he pedestal is designed so that the urine that comes in contact with the wall of the bowl is directed via wall adhesion to a trough at the bottom of the pedestal that leads to the outside'* (Rieck et al., 2012, p. 8).

Figure 17: Urine diversion pedestals (Rieck et al., 2012, p.1, 11).

Generally, the user interface should be durable, easy to use and clean, have a nice visual appearance and should not be prone to failure. Hence, materials with a smooth surface, like porcelain, fibre glass or plastic are suitable. Besides the fact that these materials are easy to clean, they are also often perceived as status symbol and their availability in different colours makes them more attractive for the users. Pedestals made from ceramic look almost like conventional flush toilets. Although plastic pedestals are often considered less durable, very positive experiences have been made in many countries (Rieck et al., 2012). Pedestals made out of concrete can be a very economical alternative to commercially available products.

Morgan (2007) exemplifies several methods for such a low-cost alternative, where a plastic bucket is used as mould and insert for the pedestal. The bottom of the bucket gets sawn off and cement is built up around the outside walls (see Figure 18). A regular plastic toilet seat is mounted on top with cement mortar. The bucket remains inside the pedestal and gives a smooth surface, which can be cleaned easily. The urine gets drained off via a plastic elbow and pipe in the front section of the pedestal (Morgan, 2007). Other construction methods for concrete pedestals can have the disadvantage of fast abrasion and a rough surface will make them susceptible to dirt and odour development (Rieck et al., 2012). As Drangert (2010, p. 1) states, '*[s]imple building errors can ruin a toilet by making it smelly or difficult to keep clean […]'.* A smooth concrete surface can be painted and periodically treated with a sealant (e.g. wax) to facilitate easy cleaning and avert these disadvantages (Rieck et al., 2012).

The second option of UD sitting toilets are benches with inserts. The insert, a flat urine diversion seat which looks similar to a squatting pan, is mounted directly onto the slab of the faeces chamber (see Figure 19). To ensure that children can use the toilet correctly, a moveable seat adapter may be necessary. Further the distance between the front edge of the bench and the seat should be as small as possible, at best not more than 5cm (Hoffmann, 2012; Rieck et al., 2012). This bench design has several advantages. The fact that the whole UDDT structure is built above ground results in a relatively tall building height. Sometimes the toilet is the tallest building

Figure 18: Construction of low-cost UDDT pedestal (Morgan, 2007, p.51, 53, adapted).

within the vicinity, which makes it highly visible, hence *'[…] visiting the toilet is not a private activity and may deter users. Another is that access for older people and invalids is difficult'* (SOPAC, 1997, p. 26). In a project report about a Composting Toilet workshop in Vanuatu Crennan & Booth (2007, p. 12) state that, *'[i]n some Pacific Island countries, the raised toilet room of the CT* [i.e. Composting Toilets] *has been a social obstacle to acceptance of the technology. However, none of the Ni-Vanuatu participants saw this as a problem, and one man said he would like to raise his flush toilet so he could have steps up it like the CT'.* The desired building height might be different for each user. In case a lower building height is wanted, this can be achieved by the bench design, which also reduces the number of stairs that are required to get inside the toilet cubicle. Assuming a vault height of 80cm and a bench height between 36 to 45cm, then only two additional steps, rather than four steps, are necessary. These can either be built inside or outside the superstructure or in a combination of both. A step directly in front of the bench can act as a convenient footrest. If the design takes advantage of the natural slope of the terrain than steps can be avoided entirely. However, if one or two steps are still necessary to reach an adequate sitting height, then this can also be achieved by constructing a small ramp instead. Thereby barrier free access for elderly or disabled people can be provided. As the bench design can easily be installed in existing housing structures, it became a popular option for indoor UDDTs. Since 2000 this design was successfully implemented in projects in Ecuador and Peru (Hoffmann, 2012; Rieck et al., 2012). Regarding construction details, Hoffmann (2012) recommends using cement reinforced with irons (8mm) for the cover slab, which acts as a bench. Alternatively, the bench can also be built with regionally available materials, like wood or reed covered with mud mortar (8cm thick) or cement. Wooden plates, with a thickness of at least 2.5cm, can also be used. These have to be made waterproof with varnish or paint (Hoffmann, 2012).

Although flies or other vectors are usually not attracted by dry faeces, it is recommended to cover the faeces drop hole with a tight-fitting lid. The installation of a lid not only avoids a potential infestation but also assures that no water accidentally enters the chamber. This is particularly relevant for toilets with a squatting pan and an anal washing basin. However, pit latrine users are commonly used to uncovered drop holes. Hence a UDDT design without a lid can make using the toilet more straightforward. Covering the inactive vault with a semi-permanent lid, that is hard to remove, indicates clearly that the chamber is currently not in use, what will prevent an accidental misuse of the wrong chamber. Lids can be beneficial in regard of odour control, albeit if the toilet is designed and operated correctly there should be very little or no smell coming out of the vaults (Rieck et al., 2012).

Figure 19: Inserts for urine diversion sitting toilets (bench style) (Hoffmann, 2012, p. 2, 14, 17, adapted).

7.5.2 URINAL

In the beginning the acceptance of UDDTs can be low, as their utilization is not intuitive or apparently clear to some users. Beside demonstrations and trainings for correct use of a UDDT, the installation of a urinal can raise the acceptance and forestall misuse (urinating into the faeces drop hole) of the toilet (Tilley et al., 2014). This wetting of the faecal content must be prevented as it impedes the desiccation process and results in the formation of odours (Rieck et al., 2012). Urinals are usually used by men. However, they *'[…] can have a large impact on the well-being of a community. When men have access to a urinal, they may urinate less often in public, which reduces unwanted odours and makes women feel more comfortable'* (Tilley et al., 2014, p. 49).

Urinals for women are also available, but these are not very popular due to several reasons. One important aspect is that women have to partially undress to use the urinal, thus they have a higher need for privacy (Münch & Dahm, 2009). For women, urinals used while standing are usually made up of a sloped catchment area and raised foot-steps. Male urinals can be constructed as squatting pans on the floor or as vertically wall hung units. A urinal can be built separate or attached to the toilet cubicle. If the space is large enough it can also be constructed inside the cubicle, but only if the user is not disturbed while sitting on the toilet. This option is usually favoured by households, as it is convenient and cheaper (Rieck et al., 2012). Urinals can be operated either with or without flushing water. The use of water can have the advantage of easier cleaning and limited odours due to a water seal (Tilley et al., 2014). However diluting urine with water results in several drawbacks, which are discussed in the chapter 7.6. Waterless urinals, which allow the collection of undiluted urine, are becoming increasingly popular. The main benefit of these urinals is that they save water and costs. As there is no need for flush water piping or other flushing devices, a significant cost reduction is possible. A second major benefit is that the undiluted urine can be used as good agricultural fertiliser. Further the recycling of phosphorus from urine is easier when it is not diluted (Münch & Dahm, 2009).

The wall where the urinal is mounted should be covered with materials which allow easy cleaning, like linoleum or tiles (WECF, 2015). Urinals are usually built from ceramics, acrylic, glass-fibre reinforced polyester or stainless steel. Yet it is possible to self-build them out of low-cost plastic or concrete, as long as the surface is smooth (wax coating) (Münch & Dahm, 2009). For plastic urinal bowls Münch & Dahm (2009, p. 5) recommend *'[…] to use linear low density polypropylene as it is among the most inert plastics (non stick surfaces). The hot production process at 180° guarantees a smooth, non porous surface, therefore minimising bacterial biofilm growth'.* It can also be feasible to turn a regular water-flushed urinal into a waterless one. This depends on the bowl design and if the water trap can be replaced by another odour control device (Münch & Dahm, 2009; Rieck et al., 2012). Since there is no behaviour change required for the users, the acceptance of waterless urinals is the same as for water flushed urinals. However, there is sometimes still the misconception that water is equal to hygiene and therefore a urinal can only be hygienic if it is flushed. These concerns can be quickly averted by the implementation of well-functioning, odourless demonstration projects (Münch & Dahm, 2009).

7.5.3 Odour control measures for Urinal/User interface

Regarding odour control, waterless urinals have to meet the standards of water-flushed urinals by emitting less or at worst equally as much smell. People are used to smelly conventional urinals, but any odour coming from a waterless urinal will get blamed on the new system, decreasing its acceptance. To enable odour-free operation the following four guidelines must be considered. Smell coming back through the drainage pipe must be blocked by an appropriate device (e.g. rubber tube seal, curtain valve seal, sealant liquid). The surface of the urinal bowl must be smooth and non-sticky. Gaps at the connection of the urinal and the drain fitting must be kept minimal to avert accumulation of urine. Cleaning of the urinal bowl and maintenance of the odour blocking device must be conducted regularly (Münch & Winker, 2011). The urinal bowl should be designed like a funnel, thereby enabling the urine to drain directly and prevent the formation of odours (Drangert, 2010). A proper odour seal for waterless urinals is important for user acceptance, especially in badly ventilated situations like indoor settings (Rieck et al., 2012). Several odour control measures for the connection of a waterless urinal to a sewer or storage tank are available.

The rubber tube seal is a small hose, which is flat at the bottom end and acts as a one-way valve. It opens when urine is passing through, but when not in use it sticks together, and blocks odours emanated from the sewer or storage tank. Urine precipitates inside the tube must be regularly cleaned out with water. Aggressive cleaning agents, which can damage the rubber material, should not be used.

The curtain valve seal (e.g. EcoSmellStop) uses the same concept but requires less maintenance. A small pressure difference is used to dispense the urine over the whole inner surface of the tube, thus reducing the formation of precipitates by flushing the inside of the unit. The silicon tube is surrounded by a plastic casing. This allows a quick and easy replacement, which is usually necessary once per year. The whole unit can be removed with a plastic extractor tool, without the need to touch it by hand.

The third commercially available option works with biodegradable sealant liquids (blocking fluids). These are either vegetable oils or aliphatic alcohols, with a relative density around 0.8. Hence the fluid, which is contained in a trap, floats on top of the urine and blocks odours from the drain below. A cartridge inside the trap, which collects urine precipitates, must be cleaned or replaced regularly. Moreover, refilling the sealant liquid may be necessary occasionally. This can also be done with a thick cooking oil, although it will not last as long as the recommended fluids (Münch & Winker, 2011). For simple, small-scale systems, some other odour control methods can be practicable (see Figure 20).

A low-cost version of the rubber tube seal is to put a condom with the tip cut off into the urine pipe. Another method called 'eco-lily' consist of a round light bulb or plastic ball, which is placed into a funnel or something similar which reduces the diameter of the pipe to hold the bulb or ball in place. This simple method acts as a one-way valve. The bulb or ball floats up when urine is passing through and subsequently seals the urine drain against odours coming back via the pipe.

Figure 20: Low-cost odour control measures for waterless urinals or UD toilets (WECF, 2015, p. 34, adapted).

If water-flushed urinals are transformed to be used as waterless urinals, then a simple odour control method is to seal all but one or two outflow holes inside the bowl. Thus, less smell can get from the pipes into the toilet cubicle (WECF, 2015; Rieck et al., 2012). Another low-cost option is to put a mesh bag of charcoal into the urinal bowl. Charcoal can absorb urine odours, but it must be replaced at times. If easy access for maintenance or replacement is possible, then some of these measures can also be used for other dry toilet user interfaces like pedestals, inserts or squatting pans (Rieck et al., 2012). The functioning of any odour seal method should be controlled regularly (Tilley et al. 2014). If the toilet is well ventilated and operated properly (e.g. use of cover material) and if there is some basic odour control for the urine storage system (see chapter 7.6.3) then these methods at the user interface may not be required (Rieck et al., 2012). Kvarnstroem et al. (2006) state that an odour seal is not necessary in case of small systems with only one toilet or urinal, which are connected to a short piping system with good slope.

7.6 Urine collection system

7.6.1 General design aspects

Basically, the urine collection system is designed to enable the drainage of urine without flushing water. Moreover, the formation of blockages and odours should be reduced to a minimum and in case of urine storage, the operation should be easy and simple. The discharged urine can either be infiltrated directly on-site, discharged into an Evapo-transpiration Bed, transferred into a sewer or stored in a tank for reuse or off-site disposal. The fact that the urine is not mixed with water results in multiple benefits. If the urine is stored, then undiluted urine requires less storage volume (smaller vessel/tank) or less frequent emptying. Moreover, the sanitisation of undiluted urine during the storage time is more effective because the increase in pH is more distinct (Rieck et al., 2012). According to the WHO guidelines (2006, Vol4, p. 39) *'[…] lower temperature and higher* *dilution result in longer survival of most bacteria'* in stored urine. The formation of smell is also decreased if urine is not mixed with water (Drangert, 2010). If the urine is drained through a piping system, then the dilution with water facilitates the formation of urine precipitates, leading to obstructions (Udert et al., 2003). Though, mixing urine with greywater is feasible if it is used for irrigation on household level, which does not necessarily demand for treatment through storage. If a urinal is used, then its urine collection system can either be joint or separate from the UDDT (Rieck et al., 2012). The urine collection system is usually designed as one of the following options:

- Pure urine gets directly disposed of on-site via infiltration trenches or soak pits.
- Pure urine is collected and stored in containers for subsequent use in agriculture or off-site disposal.
- Urine is mixed with greywater or anal cleansing water and discharged either into a sewer, soak pit, constructed wetland or irrigation system (Rieck et al., 2012).

The piping system can either be built with rigid pipes or soft hoses. Due to easy installation and changing in case of defects, Deegener et al. (2006) recommend using hoses for the squatting pans and pedestals. When using hoses, it is reasonable to decrease the diameter directly under the user interface with a metal-tube ring to about 10mm. This will impede bad odours from getting into the cubicle through the piping system (Deegener et al., 2006). On the contrary Rieck et al. (2012) advise using stiff pipes or spiral coiled tubes with a smooth inner surface. Flexible hoses with thin walls are likely to form sharp bends and might get blocked more easily due to their small diameter (Rieck et al., 2012). Since urine is very corrosive due to its ammonium content, metals should be avoided in the piping system. Hence it is recommended to use pipes made out of Plasticised PE, polypropylene (PP), polyvinyl chloride (PVC) or unplasticised PVC (uPVC). Care must be taken if the pipes are exposed to sunlight, as the UV radiation makes plastic pipes brittle resulting in material defects. Hence UV resistant paint should be applied on sections exposed to direct sunlight (Kvarnstroem et al., 2006; Rieck et al., 2012).

If the urine has time to stand in the pipes, then smell is generated as the urea in the urine degrades into ammonia (Rieck et al., 2012). The enzyme urease, which accumulates in sections where the urine flow velocity is low or stagnant, quickly degrades the excreted urea to ammonium and carbon dioxide (see Equation below).

urea water urease ammonium hydroxide carbonate

$$CO(NH_2)_2 + 3\,H_2O \quad \rightarrow \quad 2\,NH_4^+ + OH^- + HCO_3^-$$

The produced hydroxide ions usually increase the pH to 9-9.3. The urine contained phosphate, magnesium, calcium and ammonium precipitate due to the high pH-value. As a result struvite ($MgNH_3PO_4$) and apatite ($Ca_{10}(PO_4)_6)(OH)_2$) are formed, which leads to the generation of sludge (Jönsson et al., 2004). Larsen & Lienert (2007, p. 9) state that this process is more pronounced in case of undiluted urine, as *'[...] hydrolysis of only 8 % of the urea is sufficient to increase the pH to almost the maximum value, with 95 % of the possible precipitation being attained as a result'*. As a consequence, either hard precipitates (incrustations also called 'urine stone') or soft, past-like precipitates (deposits) are formed. Incrustations tend to occur on the inner walls of the pipes, whereas soft deposits usually form a sludge layer at the bottom of storage tanks or in almost horizontal pipes. In waterless systems the appearance of soft deposits is more likely. On the contrary hard incrustations are more common in water-flushed UD systems (Münch & Winker, 2011). At the same time a viscous and slimy layer, which facilitates the formation of blockages, can develop in the pipes (Rieck et al., 2012). In general, it is expedient to design the piping system for good slope and velocity in order to avoid crystallization and settling of salts in the urine. If bends are unpreventable, it is better to install two 45° bends instead of one 90° corner. On the one hand, right-angled bends would reduce the velocity of urine to almost zero. On the other hand, they are more difficult to clean with mechanical devices (Drangert, 2010). Openings should be positioned at critical bends, to enable inspection and cleaning activities. Pipe connections must be water tight, which can be achieved with rubber rings or sealant glue. Moreover, the piping system should be as short as possible and negative slopes must be avoided in order to prevent sedimentation pockets. The dimensioning of the pipes depends on whether the toilet is equipped with a u-bend or not. Small systems, with only one toilet per urine pipe, do not necessarily need a u-bend. In this case, thin pipes with a minimum diameter of 25mm and a slope of at least 4% can be used. If there is a u-bend in the toilet, then the diameter should be at least 75mm and the slope at least 1% (Kvarnstroem et al., 2006). Pipes with greater diameter (> 75mm) should also be used where access for maintenance purposes is difficult (Tilley et al., 2014). As a general rule Rieck et al. (2012) recommend using pipes with a minimum diameter of 50mm and a slope of at least 5%. The urine pipes should be installed as vertical as possible to inhibit crystallisation (Drangert, 2010). Blockages in the urine outlet or piping are a common and serious defect, which results in bad smell and renders the system unusable. These can also occur due to wrong operational behaviour like dropping cover material, waste products or faeces into the urine section. The risk of blocked pipes can be reduced by following some additional design rules. The urine outlet in the user interface should have a diameter of 1-2.5cm. Hence large objects cannot get into the piping system. Further a small outlet hole indicates that it is not the faeces drop hole. The installation of a coarse sieve or mesh inside the urine section can prevent clogging of the pipes with foreign objects. Additionally, it visually implies a liquids-only section. The drawback of using a sieve is increased maintenance effort, as it requires daily cleaning (Rieck et al., 2012).

7.6.2 DISPOSAL OF URINE ON-SITE

The reuse of urine might not be intended or possible due to several reasons, like distance to agricultural fields, land limitations or social and cultural restrictions. Infiltrating urine into the soil can be a suitable approach, provided that the groundwater is not used as source of drinking water or that the risk of groundwater contamination is marginal. Under these preconditions on-site infiltration is the simplest option of urine management. It does not require any storage, treatment or transportation of urine. Nevertheless, the feasibility of urine infiltration depends on conditions like the absorptive capacity of the soil and the local groundwater level. The on-site infiltration of urine can be done via a soak pit or subsurface infiltration trench.

Soak pits are covered or uncovered, underground chambers with porous walls, which allow a slow percolation of liquids into the surrounding soil. Two different options are possible for the construction of the chamber. They can either be left empty and lined with porous material to prevent collapse of the structure, or they are unlined and filled with coarse rocks and gravel to ensure stability. In any case the bottom of the pit should be covered with a layer of fine gravel or sand to distribute the flow evenly. Depending on the anticipated volume of urine, the absorptive capacity and hydraulic conductivity of the soil, the depth of a soak pit should be between 1.50 and 4.00m. The construction of a low ring beam above ground allows to clearly demarcate the location of the pit. A removeable lid, often made from concrete, is beneficial to seal the chamber against foreign objects and allows access in case of necessary maintenance work.

Another option for dispersing urine into the soil is via an infiltration trench. Basically, it is a perforated pipe with a diameter of approximately 5cm, which is laid in an underground, gravel-filled trench with a depth between 0.50 and 1.00m. The urine gets infiltrated into the soil along the length of the pipe. To avoid clogging of the diffuser pipe a layer of geotextile fabric can be placed above the gravel filling, which is then covered with sand or topsoil. Since both infiltration options are placed below ground, users and animals do not get in contact with the effluent, so there are no health risks through direct exposure of urine. Usually there are no odour problems, as long as the pit does not get clogged and urine does not accumulate on the surface (Rieck et al., 2012; Tilley et al., 2014). However, the infiltration of urine can have negative effects on the groundwater. The major concern with groundwater pollution through urine infiltration is due to elevated levels of nitrate (NO_3). These can have effects on the public health, for example causing the disease 'Blue Baby Syndrome' if the water is consumed by infants.

Unless the infiltrated urine is heavily cross-contaminated with faecal material, there should be almost no risk of pathogen transmission into the groundwater. If urine infiltration is taken into consideration, then the first step must be the analysis of current and mid-term drinking water resources. If groundwater is the only source of drinking water, then the possible consequences of urine infiltration must be identified in a detailed risk assessment, including groundwater level, soil conditions and evapo-transpiration potential of vegetation. (Rieck et al., 2012). If an in-depth risk assessment is not viable, then the infiltration should take place with a minimum horizontal distance of 30m from the next drinking water source and at least 2m above the highest groundwater level (Tilley et al., 2014). Stenström et al. (2012, p. 108) state, *'[t]here may be some risk associated with infiltrating urine directly into the ground, as it may contaminate the groundwater but these risks are small compared to the benefits of the hygiene provided with a reduced occurrence of open defecation'.*

The infiltration of urine into the ground does not comply with the basic idea of ecological sanitation, as valuable resources for plant growth are disposed of rather than reused in a closed loop. Urine contains most of the plant-available nutrients, whereas faeces contain almost all of the pathogens excreted (Höglund, 2001). In regard of the total amount of excreted nutrients, approximately 80% of nitrogen, 60% of potassium and 55% of phosphorus is present in the urine (Stenstöm, 2011). These nutrients contained in urine can be used indirectly by planting fruit trees, bushes or other plants alongside the infiltration area or by infiltrating urine close to existing vegetation. Hence not only the nutrients can be taken up by plants but also the risk of groundwater contamination with nitrate and other pollutants (e.g. pharmaceutical residues) is decreased. Evaporation and capillarity can result in drawing the urine back to the surface, which may be positive for nutrient uptake of surrounding plants, but it can also increase the salinity of the soil. This depends beside soil and climatic conditions also on the volume of urine and the size of the infiltration basin (Rieck et al., 2012).

A third option to directly dispose of urine (or other wastewater streams like greywater) on-site is through Evapo-transpiration Beds. Here the urine is discharged into a sealed receptacle next to the toilet facility. Since the bed is filled with soil and plants, the urine evaporates and transpires respectively. The nutrients are taken up by the plants and dissolved organic material is removed by soil bacteria. If the urine is discharged below the surface, then odours and the risk of disease transmission are reduced. Evapo-transpiration can be increased by positioning the bed in an area with maximum solar insolation. Evapo-transpiration Beds can be built in a wide variety of designs and at very low costs. They are particularly suitable in areas with dry and hot climate. Further they are applicable in areas with high groundwater tables as they risk of contamination is decreased (Masong & Gensch, 2019).

7.6.3 STORAGE SYSTEMS FOR URINE

Urine storage tanks or containers can fulfil several different purposes. If the urine gets transported off-site for disposal or reuse, then the tank allows longer intervals until the next pick up by a service provider is necessary. The usage of small containers makes the collected urine transportable. If the urine should be applied as agricultural fertiliser, then the storage in tanks enables the sanitisation. Tanks also allow to accumulate and store fertiliser until it is needed in agriculture (Rieck et al., 2012).

Urine storage in tanks or containers is the simplest, cheapest and most common form of urine treatment. The main objective is the killing of pathogens, which may contaminate the urine mostly due to faecal cross-contamination at the user interface (Münch & Winker, 2011). Richert et al. (2010, p. 10) state that *'[t]he amount of faecal cross-contamination is directly related to the health risk in the system for urine use in crop production. Collection systems for urine should be designed to minimize the risk of faecal cross-contamination'*. Extended storage times at ambient temperatures in closed tanks result in efficient pathogen reduction (Münch & Winker, 2011). The recommended storage time - one to six months - depends mostly on the temperature and if the urine is collected from a single household or from a large-scale system. Further it is distinguished if the urine is used to fertilise crops that are either consumed solely by household members or sold commercially (WHO, 2006b (Vol 4). *'When urine is collected from many different users as well as when the produce is sold/transferred to a third party, the microbial risk increases* *substantially. In these situations, a longer storage time should be used, rendering the used urine safer and increasing the reduction of potential pathogens present'* (Richert et al., 2010, p. 25). Urine, which is collected and reused for crops consumed only on household level can be applied directly as fertilizer without storage. In this case the risk of disease transmission among family members due to insufficient hygiene is much higher than the risk of transmission through reused urine. However, a withholding period of one month, between the last application of urine as fertilizer and the harvest should be adhered to. If faecal cross-contamination is likely, then the storage time should be prolonged (WHO, 2006). The risk of faecal cross-contamination of urine collected from urinals is insignificant. Nevertheless Richert et al. (2010) recommend, that urine collected from urinals or single household systems should also be stored. In these cases, a less strict storage time between one and two weeks can be applied, provided the urine is only used for products, which are consumed by members of the household. As a general rule, Richert et al. (2010, p. 25) state, *'[t]he longer the storage the better'*.

For these small-scale systems on household level, the urine can either be collected and stored directly in one large tank or multiple small containers or collection and storage is done separately in different vessels (Tilley et al., 2014). Depending on the amount of produced urine respectively the number of UDDTs connected to a communal storage tank, Rieck et al. (2012, p. 23) distinguish the following three typical configurations of urine storage systems:

- For a single household UDDT two or more 20L containers are alternately filled and stored for a short while (one week to one month) and finally used as fertiliser for the users' crops.
- For several UDDTs two medium sized (e.g. $1m^3$) containers are alternately used. In this case the storage time has to be longer (more than one month).
- For many UDDTs a large storage container (e.g. $5m^3$) can be shared. Emptying and transport of urine to an off-site storage facility can be carried out by an external service provider.

Jerrycans, light plastic containers, are a common option for collection, storage and transport of urine. Using transparent containers enables easy determination of the urine level, which is important to change or empty the tank in time. Cans with a volume of 20L are widely available and are easy to handle by one person. Moreover, they are cheap and can be cleaned easily. On the downside they fill up quickly, which requires frequent exchanging or emptying. Therefore, the usage of large storage tanks can be expedient. After an adequate storage time the urine can be transported to agricultural fields. (Tilley et al., 2014; Rieck et al., 2012). In order to achieve adequate sanitisation, stored urine must not be mixed with fresh urine before it is used as fertiliser. Hence it is recommended two use at least two tanks (one receptor tank and one storage tank) (Münch & Winker, 2011).

Large containers are more convenient as they require less frequent emptying, but usually they are more expensive than small tanks. If large volumes are necessary, a cost reduction can be achieved by reusing rainwater tanks, plastic drums or former septic tanks for urine storage.
The tanks for urine storage must be completely watertight to avoid loss of fertiliser and contamination of groundwater. Furthermore, they should be closed with tight-fitting lids in order to avoid odours and loss of nitrogen through ammonia evaporation. Ventilation of the piping system and the tank should not be installed due to the same reasons (Münch & Winker, 2011). Moreover, sealing the tanks or containers avoids, that humans and animals get in contact with the urine (WHO, 2006, Vol4). Pressure equalisation of the tank is necessary to allow the replacement of air with urine flowing into the tank and to allow air into the tank in case of emptying. This can be achieved by making a small hole into the top of the tank (Münch & Winker, 2011). Organic sludge and precipitated minerals accumulate and form a layer on the bottom of the tank. Therefore, the opening of the tank must be wide enough to allow proper cleaning (Tilley et al., 2014). Usually the tanks are made out of glass fibre reinforced plastic, PE, PP or PVC. Metal is not appropriate due to the strong corrosive character (high pH-value) of stored urine. As the tanks have to be emptied regularly, easy access is crucial. Depending on climate, soil and available space the tanks can either be placed above or below ground (Tilley et al., 2014; Rieck et al.,

2012). Usually underground tanks can be constructed cheaper but leaks in the tank are difficult to recognize. Leaking tanks can pollute the groundwater with ammonia and nitrate or can lead to a filling of the tank with groundwater. Moreover, it is important to consider the groundwater level, in order to prevent floating tanks if the water level rises (Münch & Winker, 2011). The position and level of the tank is also crucial to ensure sufficient slope for gravity flow in the pipes. Large containers can be equipped with a urine overflow pipe leading into a soak pit (Rieck et al., 2012). Nevertheless, Münch & Winker (2011) do not recommend the installation of urine overflow pipes as it raises the costs. Furthermore, the installation of an overflow device can result in users neglecting the regular emptying or usage of urine in the tank and just letting it overflow. Instead a portable wastewater pump should be used to dispose of some urine to an acceptable site if the tank gets too full (Münch & Winker, 2011). However, positioning the tank on top of a soak area allows infiltration in case of unexpected overflow (Rieck et al., 2012).

Depending on the location (above or below ground) and the size of the tank, different methods for emptying or urine withdrawal are necessary. A simple option to manually drain urine from above-ground tanks is to use a flexible hose, which is connected to the bottom of tank. The hose, which has to be longer than the height of the tank, is lifted and tied up above the maximum urine level in the tank. To withdraw urine, the end of the hose is lowered under the current urine level. Alternatively, plastic water taps can be installed. These are often used for large above-ground tanks. They should be manufactured properly and shaded against constant UV radiation, to avoid breakage or material fatigue. Large underground tanks can be emptied with vacuum trucks. Emptying of smaller underground tanks can be done with plastic or metal hand pumps. By flushing the pump with water after each use, corrosion of metal parts can be limited (Rieck et al., 2012).

In general, the total required storage volume can be calculated with the following formula (Münch & Winker 2011):

$$V_{total} = N_{users} * p_{urine} * t_{storage} * f_{timefraction}$$

N_{users} = number of users
p_{urine} = specific urine production per day
$t_{storage}$ = desired storage time
$f_{timefraction}$ = fraction of time that the users stay at the premises where the toilet is

An adult person produces between 0.8 and 1.5L of urine per day, children produce about half the amount. The quantity depends especially on the amount of consumed liquids, activity level, climate and perspiration (WHO, 2006b). Chapter 8.2.2 provides an estimation of the required urine storage volume for the designed UDDT on Emae, Vanuatu.

Inadequate designed urine storage systems may entail odour problems. Unpleasant smell in urine collection or storage systems occurs, when urine is exposed to air and thereby the contained urea gets degraded into ammonia, which has a strong odour. This happens if the urine is stagnating in the pipe due a negative or insufficient slope. If the urine gets collected and stored in containers, then there can be problems with odours, as the discharged urine replaces air in the tank (pressure equalisation), which might result in odours getting into the toilet cubicle. Hence the following design recommendations should be considered. By mounting the urine inlet pipe close to the bottom of the tank, a liquid seal is formed inside the pipe. Due to the fact that the urine collection pipes and the tank are never absolutely airtight, the location where the tank is placed should be well ventilated. Ventilating the tank itself should only be done, if the urine is not used as fertiliser because lots of contained nitrogen will be lost to the atmosphere through the evaporation of ammonia. Using conventional water seals, like a p-trap or u-bend, where the urine acts as a seal, are not recommended due to their proneness to blockages and clogging (Rieck et al., 2012). Alternatively, some cooking oil can be poured into the storage tank, to act as a blocking fluid floating on top of the urine. Single outdoor UDDTs are usually directly connected to the storage tank, without the need for odour blocking measures (Münch & Winker, 2011).

7.7 RESULTS OF DESIGN ASPECTS OF UDDTS

A robust, above-ground substructure is important to withstand flood events and impede ground- and surface water contamination. Constructing a solid, concrete foundation prevents the structure from collapse or from sinking into unstable (e.g. sandy) soil. If the highest expected flood level lies above the height of the slab of the dehydration vaults, then the foundation can be extended to act as a raised plinth. Since the treatment of faecal matter in UDDTs is based on desiccation, special attention must be paid to sustain dry conditions inside the chambers. Vaults made of concrete ensure waterproofness in case of flood events and prevent groundwater contamination.

On-site research showed that vault doors are a common weak spot of sanitation facilities in Vanuatu. In general vault doors should be designed vertical rather than inclined. By constructing semi-permanent vault doors of concrete, which are temporarily sealed with mortar, water tightness of the access holes can be attained. Nevertheless, a constant supply of sealing material (e.g. mortar) must be ensured, and users must be trained to adequately reinstall the doors.

To avoid flooding of the facility, the topography of the area must be considered during the site selection. Due to the fact that properly operated UDDTs do not emit odour, they can be built adjacent to or inside the house. Since these are usually built on elevated terrain the risk of flooded toilets is decreased. In case the flood water level still reaches up to the height of the slab, the user interfaces can be temporarily removed, and the holes can be covered and sealed. Thus, the vault content stays dry and pathogens will not be spread in the environment. Further it is important to design the vaults large enough considering the expected number of users and the minimum storage period. If the recommended storage time inside the vault is adhered to, then no post treatment (e.g. composting) of the faecal material is necessary. Therefore, the risk of flooded post treatment sites, resulting in pathogens being spread with flood water, is avoided.

Ventilation pipes were identified as second main flaw of Composting toilets in Vanuatu. Since these are crucial for the desiccation process inside the vaults, their design and construction should not impede a constant airflow, and rainwater must not enter the pipes. The superstructure must be large enough, airy, well-lit and in accordance with the user's income and customs. This allows proper ventilation and increases the attractiveness of the facility. The tall building height of UDDTs can be an impediment to acceptance. This can be avoided by the bench style design, which decreases the height of the facility and allows easier access for elder or disabled people. Moreover, simple measures like sealing surfaces (i.e. slab or floor) with water- repellent paint can be applied at low costs but facilitate operation and maintenance and thus may increase the appreciation of the facility. A corrugated metal roof enables rainwater harvesting, so the toilet could serve a second purpose, which might also raise the acceptance.

The user interface must be durable, visually appealing and easy to use and clean. Further it must be designed to minimize the risk of faecal-cross contamination and avert urine from splashing into the dehydration vaults. The installation of a urinal can raise the acceptance of the toilet and prevent misuse. Several odour control measures for the user interface (e.g. charcoal bags or eco-lily) can be installed at virtually no costs.

The piping of the urine collection system must be designed to prevent obstructions due to the accumulation of precipitates. Using pipes with adequate diameters and constructing for sufficient slope enables higher flow velocities and reduces the risk of blockages.

Urine can either be stored for reuse or directly disposed of into the soil. If there is a need for fertilizer, then storage in small containers is the simplest form of treatment, resulting in a sanitisation of urine. The risk of faecal cross-contamination of urine used as fertilizer can be avoided by collecting urine solely from the urinal. The infiltration of urine into the soil involves the risk of groundwater contamination, depending on the local geomorphologic conditions. Low-cost Evapo-transpiration Beds can be a useful alternative to safely dispose of urine in areas with high groundwater tables.

8. TECHNICAL PLANNING OF UDDT AND POUR-FLUSH LATRINE FOR PILOT SITE

8.1 PILOT SITE – EMAE, VANUATU

The island of Emae was chosen as potential pilot site based on consultations with Jake Ward, the former programme coordinator of Oxfam Vanuatu. Four coastal villages (Finonge, Tongamea, Makatea and Reisu, see Figure 21) were visited and inspected in regard of the prevalent conditions (i.e. high groundwater, flood prone area, limited water supply). Additionally, interviews with the chiefs of Finonge (James Willie), Tongamea (David Maripu) and Reisu (Jeffery Pakoa) and with one member of the local WASH committee from Makatea (Christopher Daniel) were conducted. Moreover, the concept of urine diversion and excreta reuse was presented to the interviewees and further to a group of interested people from different villages.

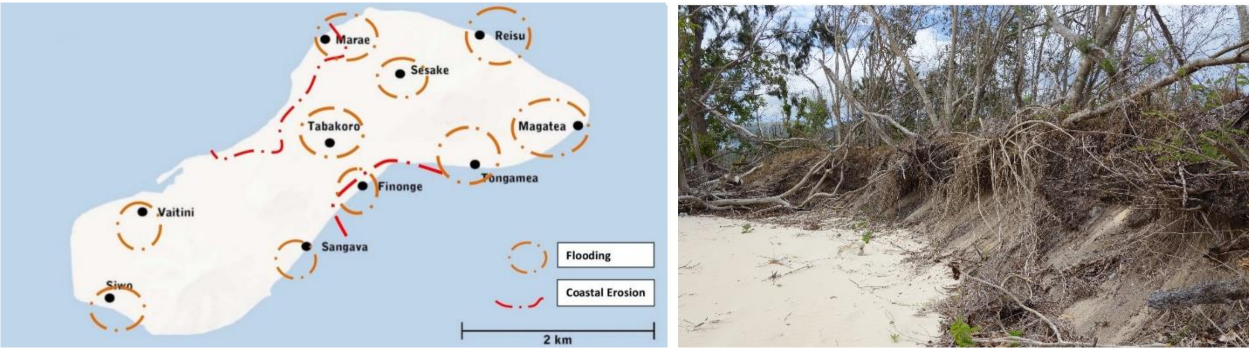

Figure 21: Villages on Emae and areas affected by floods and coastal erosion after TC Pam in March 2015 (left) (Shefa Provincial Government Council, 2015, p. 3); Coastal Erosion (right).

Emae is part of the Shepherds Islands group, belonging to the Shefa Province. The 32 km² large island is located approximately 50km north of the main island Efate. Like most islands in Vanuatu, Emae is also of volcanic origin, with volcanic sand covering most of its land area. Most inhabitants (population: ~ 900 people) live in small villages in coastal areas. Subsistence farming, with domestic animals (cattle, pigs and goats) and gardening plays an important role (Shefa Provincial Government Council, 2015). The most common plants, that people cultivate in their home gardens are taro, yam, cassava, sweet potatoes, tomatoes, cucumber, cabbage, lettuce, beans, capsicum, carrot, pumpkin, corn, banana, pineapple, papaya, peanut, sugar cane, kava and tobacco (Christopher Daniel, 2015, personal comm., December 1). Beside farming, people also depend on regular food imports from Efate. Copra made from coconut palm trees is one of the main sources to generate income revenues on the island. Families spend most of their income for school fees and household expenses. According to the local health centre the most frequent diseases are flu, and diarrhoea.

Emae does not have any rivers or streams but it does have spring water. Some of the springs were tapped with underground wells or borehole water pumps (see Figure 22, left). However, the water supply of most households depends on rainwater collection (see Figure 22, centre) (Shefa

Figure 22: Springwater-fed tap (left); Rainwater harvesting incl. a ferrocement and a polyethylene tank (centre); bush toilet (right).

Provincial Government Council, 2015). According to a Unicef Census form 2009, 90% of the households on Emae rely on rainwater harvesting (Jake Ward, 2015, personal comm., November 3). Many houses are covered with corrugated iron roofs to enable rainwater harvesting. The water is stored in big tanks (ferrocement, polyethylene or fibreglass) or small containers. Households without iron roofs rely on water stored in community tanks, financed by donors.

In March 2015 the severe tropical cyclone 'Pam' hit the island. In many villages most of the houses were destroyed and roads were unusable due to blockage by big logs, landslides and debris transported from flood waters. Figure 21 shows the areas that were affected by floods and erosion, most are located in the low-lying coastal zones. Agricultural root crops and coconut palms along the coast line were mostly destroyed (Shefa Provincial Government Council, 2015).

In the following the four villages, that where visited during the on-site research, are described in more detail. Finonge village consists of 27 households, a health centre and the Worarana & Nofo Primary and Junior Secondary School with approximately 270 students. A groundwater assessment was carried out by Oxfam, which revealed that the groundwater resources are contaminated. Water from hand dug wells and hand pumps must be boiled prior to consumption. Hence it is used solely for cooking and washing. The only drinking water source is rainwater harvesting. Usually it is not treated before consumption. In the 9 months between TC 'Pam' and the interview, no substantial rainfall occurred. During the dry season water reserves in the village run short. The groundwater level is strongly influenced by the tides. Despite the absence of precipitation for several months, the groundwater levels in three hand dug wells were between 1 and 2m. Oxfam plans the installation of an indirect gravity feed system with a solar water pump to distribute the groundwater to 10 taps throughout the village and school.

In total there are 24 toilets in the village, 16 'Bush Toilets' (see Figure 22, right) and 8 Pour-Flush. Most households have a private toilet, only a few use a shared facility. During the two last major flood events, in 2010 and in the course of TC 'Pam' in 2015, most of the toilets were inundated and overflown. Moreover, many gardens were destroyed resulting in a complete loss of harvest (see Figure 23).

Depending on the size of the land a family owns, they often have more than one farming garden. Road markets for selling crops from home gardens, are one of the few possibilities to generate income on the island (James Willie, 2015, personal comm., December 2).

Tongamea village consists of 34 households, most of them have a private sanitation facility. 80% of these toilets are Pour-Flush and the rest are basic 'Bush Toilets'. The pits of the toilets are usually dug 2.5 – 3m deep. As in the other villages it is common practice that full pit latrines are abandoned. Then the whole facility is moved to a different location and a new pit must be excavated. The groundwater level in the village is between 3 and 4m. According to an assessment by Oxfam, the groundwater is contaminated and not safe for drinking. Like in the other villages it is only used for washing and cooking. Rainwater harvesting is the only drinking water source, but during the dry season water is scarce. Like in Finonge, Oxfam plans the installation of a solar power pump to distribute groundwater to taps. David Maripu, the chief of Tongamea, was very interested in the concept of UDDT and in his opinion people would like this type of toilet. He found

Figure 23: Flood events in Finonge village: left) after persistent rainfall in 2010, right) two days after TC Pam in 2015 (Marie Willie, 2010; Marie Willie, 2015).

it especially appealing, that this type of toilet can be built adjacent to the house. David thought it would be beneficial to introduce a pilot project to collect some practical experience and demonstrate the benefits of reusing urine and faeces (David Maripu, 2015, personal comm., December 1).

The third village, Makatea, consists of 10 households. Only one of them is using a VIP toilet, the remaining 9 facilities are all ‘Bush Toilets’, with a pit depth of approximately 1.5m. The main source for drinking water is a direct gravity feed system, tapping water from a spring uphill. The system, which was rehabilitated by Oxfam in July/August 2015, distributes water to 4 taps throughout the village. Christopher Daniel, a member of the local WASH committee in Makatea, explained that during the last dry season the water supply was very limited. Hence the spring water taps were only opened twice a week and each household could fetch one jerry can with 25L. The second water source (groundwater) is only used for livestock and watering plants in the home gardens, but it has to be carried several hundred meters from a hand dug well outside the village.

Reisu is the smallest of the four villages, with only 4 households sharing a ‘Bush Toilet’. As in Makatea, Oxfam built a gravity feed system to distribute spring water to two taps in the village. Jeffery Pakoa (chief of the village) really appreciated the concept of UDDT. He stated, that it would be a great benefit for the local community if they do not have to dig new pits anymore, which is usually necessary every other year (Jefery Pakoa, 2015, personal comm., December 1).

The concept of UDDT and reuse of urine and faeces was presented to a group of people, including chiefs and members of the WASH committees from several villages. In general, the attendees were very interested in this new type of sanitation system. Recently Oxfam held sanitation workshops in the community, where people decided on whether they want to upgrade their current facilities or built a new Pour-Flush latrine. After learning about the benefits of UDDTs, several people stated that they would like to reconsider their choice and opt for the new UDDT system.

The common statement from previous interviews with sanitation experts from several NGOs in Vanuatu, revealed that Vanuatu people generally have no reservations regarding the handling of urine or faeces. This was confirmed during the meeting, as people were keen on learning about how to operate UDDTs and about possibilities of fertilizing crops with urine. In general, the concept of urine diversion and reusing human excreta is hardly known in Vanuatu. Nevertheless, when this concept was introduced to communities and interviewees from different islands (i.e. Efate, Emae, Espiritu Santo and Pele), the responses were very positive. In regard of the important role of subsistence farming and selling homegrown produce at local markets, the possibility of using urine as fertilizer was especially well received.

The island Emae would be an adequate site for a pilot project. As depicted above the defined environmental conditions (i.e. high groundwater level, flood prone area and limited water supply) are all present in this area. Moreover, it can be assumed that the groundwater contamination is a result of the current single pit sanitation facilities (‘Bush Toilets’ and Pour-Flush). These systems are not well suited for the prevailing conditions (see chapter 6.2.1).

8.2 Technical planning of UDDT for Emae, Vanuatu

8.2.1 Overview

The planned facility is a Double Dehydration Vault Urine-Diverting-Dry-Toilet, which is designed as bench style (see Figure 24). It features a foundation and a substructure made of concrete and a timber superstructure. Urine from the main user interface gets discharged into an Evapo-transpiration Bed. Urine from the urinal gets collected separately and is stored in small jerrycans.

Figure 24: Drawing of Urine-Diverting-Dry Toilet.

8.2.2 SUBSTRUCTURE OF UDDT

DEHYDRATION VAULT: In a first step the required dehydration vault volume is estimated. The calculation is based on the following assumptions:

- Since the average household size in Vanuatu is 4.8 people/household the calculation was done considering 5 people (3 adults and 2 children) (VNSO, 2011a).
- Assuming a high fibre diet, adults defecate 0.4 and children 0.15kg/day (Rieck et al., 2012).
- The minimum storage time is one year for the climatic conditions prevalent in Vanuatu (Australian Bureau of Meteorology & CSIRO, 2011a; WHO, 2006a).
- Toilet paper gets disposed of into the vaults.
- The annual average toilet paper use is 8.9kg/person/year (Rieck et al., 2012).
- The assumed average of required cover material is 0.05kg/person/day (Rieck et al., 2012).

- The density of faeces is assumed to be 1kg/l (Rieck et al., 2012).
- 20% is calculated for the time members of the household are absent and do not use the toilet at home.
- The volume reduction of the faeces in the vault due to dehydration is assumed to be 25% (Rieck et al., 2012).
- A safety margin of 25% is applied to account for visitors, uneven distribution of the faeces, potential extended storage periods and a buffer between the top of the faeces pile and the bottom of the bench/slab.

The result of the calculation for the required vault volume is 575L per vault. The inner dimensions of each vault are 0.90 x 0.80 x 0.80m. Hence the total volume of each vault is 0.576m³. The total outer height of the vault is approximately 1.0m including a base plate and slab, each with a thickness of 0.07m and the mortar in between the concrete blocks. Hence it should ensure to keep the content of the vault dry during flood events, especially if the toilet is built in elevated terrain. Since a correctly operated UDDT emits no smell, it can be built directly adjacent to the house, which is usually built on higher ground. The highest flood level in this area was approximately 1.00m (see Figure 23). This occurred in 2010, after four days of heavy rainfall (James Willie, 2015, personal comm., December 2).

CONCRETE BLOCKS: For the planned design size of the substructure 74 concrete building blocks with a size of 40x20x15cm are necessary. The blocks can be manufactured directly on site, using a mould. This method is commonly used for house construction on the island (see Figure 25) (James Willie, 2015, personal comm., December 1).

Figure 25: Mould and self-made cellular concrete blocks.

The required volume of concrete for the production of each cellular block is approximately 0.0064m³, which sums up to 0.475m³ for all blocks. However, when mixing concrete, the sum of the ingredient volumes (i.e. cement, sand and coarse aggregate) is greater than the volume of the final mixture, as the sand fills the voids between the coarse aggregate. For all following concrete calculations this volume reduction is considered with 30%, 5% are considered for waste and the density of cement is determined with 1351kg/m³ (Bengtsson & Whitaker, 1988). Assuming a concrete mixture of 1:3:6 (1 part cement, 3 parts sand, 6 parts aggregate) 96.30kg of cement are required in total for the blocks. The other parts of the concrete mixture, i.e. sand and coarse material (e.g. crushed coral), are available abundantly on the island (James Willie, 2015, personal comm., December 1). Therefore, no costs are included for these materials in the calculation.

FOUNDATION: The foundation is built from a rectangular shaped concrete pedestal, which is 0.25m deep and 0.30m wide. The excavation for the foundation of the structure can be filled with stones and crushed coral, easily available on the island. Assuming a concrete mixture of 1:3:8 then 138kg of cement are necessary for the foundation.

FLOOR PLATE, SLAB AND VAULT FLOOR: The aggregated volume is 0.44m³ (thickness 0.07m). Using a concrete mix ratio of 1:3:3 then 134kg of cement are required. Additionally, the slab and floor plate are reinforced with 6mm thick steel mesh. To enable easy cleaning the slab surface is coated with waterproof paint. The vault access doors (0,45 x 0,60 x 0,07m) are made of reinforced concrete, with metal handles for easier detachment. Since it is required to make the vault waterproof for upcoming flood events, the doors are temporarily sealed with weak mortar.

EVAPO-TRANSPIRATION BED: The urine from the User Interface (i.e. inlet) drains into an Evapo-transpiration Bed that is lowered into the ground next to the toilet. The bed (1,00 x 0,50 x 0,35m) is out of concrete and connects through PVC pipes (diameter: 50mm) to the User Interface. It is further equipped with an underground overflow device to impede ponding during the rainy season.

To account for mortar and plastering 1 bag is added. In total 11 bags each 40kg are necessary for all concrete elements of the facility.

USER INTERFACE: The interface has to be imported, as urine diverting inlets are not yet available in Vanuatu. Since only one vault is active at a time, only one inlet (ceramic), which is always moved to the active vault, is required. The hole of the inactive vault is sealed with a wooden lid during the storage phase. The urinal can be bought at a local warehouse in Port Vila.

URINE PIPING: The pipes are also made of PVC with a diameter of 50mm. Seven 45° couplings are required to build smooth corners in order to avoid blockages in the pipes. The total length of all pipes is around 2.4m. The slope of the pipe is around 13° to ensure a proper flow velocity.

The required storage volume for urine is based on the following assumptions:

- The urine from the UDDT bench interface gets discharged into the Evapo-transpiration Bed. Hence only the urine from the urinal gets collected and stored in jerry cans.
- On average adults excrete 0.8 – 1.5L of urine per day (WHO, 2006b. In the calculation the mean value was used and rounded to 1.2L.
- Children excrete approximately half the amount, so the value of 0.6L per day was used.
- It is assumed that 2 adults and 1 child use the urinal.
- The urine storage time is 30 days.
- 20% is calculated for the time users are absent and not using the home toilet.
- 10% is added to account for visitors and safety margin.

The calculated urine storage volume is 79.2L. Hence four jerrycans with 20L each are necessary.

8.2.3 SUPERSTRUCTURE OF UDDT

The basic framework is made from wooden beams (15 x 15cm), mounted with u-shaped post anchors. The walls of the superstructure are made from wooden slats (5 x 5cm) and planks (15 x 2.5cm). The cheapest, commercially available timber option is 'Melek Tree' (from a wood supplier in Port Vila), which is used for all wood constructions in this design. The total surface area that needs to be covered (front-/side- and back-wall) is 12.00m². The door is also made of wooden planks and mounted with metal hinges.

Additionally, 1.00m² of fly mesh is incorporated at the top segment of the walls. Thereby lighting during daytime and ventilation of the cubicle is provided. At night a solar powered light, which is available in most households, can be hung up inside the cubicle. Alternatively, a permanent solar powered LED-light can be installed.

The roofing of the cubicle is made of corrugated metal (zinc) sheets covering an area of 7.00m², which can also be used for rainwater harvesting. If the natural terrain necessitates the need for stairs, then these can be made from concrete, to guarantee longevity, when facing flood events. The ventilation pipes are made of 150mm diameter PVC pipes. The total length of each pipe is 2.30m. A T-cap is mounted on top of each pipe to prevent rainwater from entering the vaults.

8.3 Technical planning of Single Pit Pour-Flush Latrine for Emae, Vanuatu

8.3.1 Overview

The second system is a Single Pit Latrine with a Pour-Flush interface (Figure 26). The lining of the pit and the slab are made of concrete. The superstructure is built of timber. This option was chosen, as it is the desired toilet system for many people in this area. Additionally, it is also the latrine that Oxfam is providing, if people want to upgrade from their basic 'Bush Toilets'.

Figure 26: Drawing of Pour-Flush Latrine.

8.3.2 Substructure of Pour-Flush Latrine

In order to prevent collapse of the pit in sandy soil, the walls of the pit head have to be lined (Morgan, 2004). Reed & Shaw (2012a) state that at least the top meter of a pit should be lined to stabilise the soil. The latrines built by Oxfam in Vanuatu are usually also lined at the top meter (Jake Ward, 2015, personal comm., November 3). It is assumed that ten rows of bricks, each with a height of 10cm, are arranged in a round shape. Below the 10 rows of lining bricks, another row is laid flat to act as a foundation in the sandy soil. The diameter of the pit is 1.00m. In total 176 concrete bricks are necessary for the construction of the ring beam. The required volume of concrete for the production of each brick is approximately 0.001m^3. Assuming a 1:3:6 concrete mixture, 36kg of cement are required to produce the concrete bricks.

Further a slab is placed on the ring beam. All toilets, that were inspected during the research stay in Vanuatu, were equipped with a square shaped slab. Hence this kind of shape is also used for the calculation. The slab is 7cm thick and made out of reinforced concrete (1:3:3). The volume of the slab is 0,10m^3, hence 31kg of cement are required. Apparently, most households in Vanuatu do not reuse the slabs of old latrines, when they are re-siting the toilet, instead a new one is built (Jake Ward, 2015, personal comm., November 3; David Maripu, 2015, personal comm., December 1). Therefore, each time the latrine is re-sited, the costs of the whole substructure (i.e. lining and slab) are included in the calculation (see chapter 9.4). The toilet pedestal can be bought at local hardware stores in Port Vila.

In total 3 bags each 40kg are necessary for all concrete elements of the Pour-Flush Latrine.

CALCULATION OF PIT LIFETIME

The pit life is the time it takes the pit to fill up. In the case of Emae the Pour-Flush Latrines are considered ‘wet pits’, since they are partly below the water table and permanently contain water. An important variable for the calculation is the sludge accumulation rate. This figure indicates how much volume of waste is deposited per person per year. Micro-biological activity is greater in wet conditions than in dry pits. Further the solids can be compacted more efficiently under water. Therefore, the sludge accumulation rate is much greater in a dry pit compared to a wet pit (see Table 8). However, these values are long-term accumulation rates for deep pit latrines, where the pit content has time to degrade. In case of shallow pits, like on Emae, these figures will be too low and should be increased by 50% (Reed & Shaw, 2012b).

Table 8: Sludge accumulation rates for pit latrines with wet or dry conditions (Reed & Shaw, 2012b, p.9, adapted).

Wastes deposited and conditions	**Sludge accumulation rate (litres per person per yr)**
Wastes retained in water *Degradable anal cleaning materials used (e.g. paper*	40
Wastes retained in water *Non-degradable anal cleaning materials used (e.g. stones, sticks)*	60
Wastes retained in dry conditions *Degradable anal cleaning materials used*	60
Wastes retained in dry conditions *Non-degradable anal cleaning materials used*	90

The calculation of the lifetime is based on the following assumptions:

- 5 people are using the latrine.
- The diameter of the pit is 1m, the depth is 2m. Since the slab is left on the old latrine it can be filled to the top resulting in a useable volume of 1.57m³.
- The sludge accumulation is 60L per person per year (40L rate for wet conditions and degradable cleaning materials + 50%, due to shallow pit depth) (Reed & Shaw, 2012b).

According to this calculation the pit life is 5.2 years. Hence it is assumed that latrines will be re-sited every 5 years. This time span is in line with estimates made by locals during the interviews.

8.3.3 SUPERSTRUCTURE OF POUR-FLUSH LATRINE

The superstructure of the Pour-Flush latrine is constructed in the same way as the superstructure of the UDDT. All timber materials are ‘Melek Tree’, with the same dimensions of the beams, slats and planks (15x15cm; 5x5cm and 15x2.5cm respectively), as used for the cubicle of the UDDT. The total surface area that needs to be covered (front-/side- and back-wall) is approximately 8.00m². A fly mesh is incorporated in the top segment of the front and side walls. A corrugated zinc sheet is used as roof and can be used to collect rainwater.

9. Financial analysis of UDDT and Pour-Flush latrine on Emae, Vanuatu

9.1 Overview

For both systems the construction costs (CapEx), operational costs (OpEx) and maintenance costs (CapManEx) are estimated to calculate the Present Value of the Urine-Diverting-Dry-Toilet and Pour-Flush Toilet. Based on the design sketches from the previous chapter, Bills of Quantity were compiled for each of the two sanitation options (see Table 9 and Table 10). These lists contain all material, transport and labour costs required for the construction. This seems to be the best approach for achieving a relatively accurate estimate of the costs of an on-site sanitation technology (Ulrich et al., 2016). Further pathways to reduce the construction costs (i.e. CapEx) are described. A second calculation with local building materials is included.

For better comparison, all values are converted from the local currency Vatu (Vt) to US Dollars, using the official market exchange rate of 108.99 Vt/US$ from 2015 (Worldbank, 2019).

9.2 Capital expenditure (CapEx)

9.2.1 Material costs

The costs for the materials were determined through inquiries at local hardware stores. Commonly NGOs in Vanuatu purchase building materials at these local stores (Jake Ward, 2015, personal comm., November 3). The costs for the user interfaces (i.e. urine-diverting insert, urinal and pour-flush pedestal) were estimated due to lack of data. The estimate for the UD insert is based on values from a worldwide listing of suppliers for urine diversion interfaces compiled by Münch & Winker (2011). The material costs are shown in the BOQ for each toilet.

9.2.2 Transport costs

The transport costs for the construction materials were calculated based on interviews with locals on Emae. These costs are mainly composed of the shipment by cargo vessel from the main island Efate to Emae. Additionally, the materials have to be transported from the dock to the pilot site via truck. The transport and cargo costs for large products (e.g. cement bags) are included individually, smaller materials are calculated with lump sum amounts.

9.2.3 Labour costs

The labour costs for the construction of a UDDT are estimated with 15000Vt (137.63 US$), based on information given by the local carpenter (Jakob Essau, 2015, personal comm., December 1). In case of the Pour-Flush Toilet, the labour costs for the construction are approximately 10000 Vt (91.75 US$) (Jake Ward, 2015, personal comm., November 3). For re-siting the facility and building a new substructure the labour costs are estimated with 5000 Vt (45.91 US$).

9.2.4 Potential for cost savings

In the following, opportunities to reduce construction costs of both systems are described. Considering the CapEx, Ulrich et al. (2016) explain three pathways which allow a cost-reduction of on-site sanitation systems: (i) design optimisation, (ii) prefabrication and mass production, and (iii) alternative building materials.

Design optimisation can include decreasing the dimensions of the toilet to save building materials. The UDDT vault volume calculation is based on several assumptions which may differ for each household. If for example a household has fewer family members, then a smaller vault requiring less material for construction, will be sufficient. However, the potential for decreasing the vault is limited by the fact that it should have a minimum height to guarantee safe containment

Table 9: BOQ (incl. material, transport and labour cost) of the Urine-Diverting-Dry-Toilet for Emae, Vanuatu.

	Item	Quantity	Unit	Cost/Unit Vatu	(US$)	Total Cost Vatu	(US$)	Cargo cost Vatu	(US$)	Labour cost Vatu	(US$)
	Cement (Dricon) á 40kg	11	bag	800	(7,3)	8800	(80,7)	5500	(50,5)		
Substructure	Sand	0,86	m^3								
	Coarse Aggregate	1,63	m^3								
	Steel mesh reinforcing 0,006x5,8x2,3	1	pcs	4675	(42,9)	4675	(42,9)	250	(2,3)		
Ventilation	DWV PVC pipe 5,6m x 150mm	1	pcs	5770	(52,9)	5770	(52,9)	100	(0,9)		
	DWV PVC pipe 5,6m x 50mm	1	pcs	2815	(25,8)	2815	(25,8)				
Urine Collection	DWV PVC pipe coupling 45°	1	pcs	825	(7,6)	825	(7,6)	900	(8,3)		
	DWV PVC pipe bend 50mm 45°	7	pcs	310	(2,8)	2170	(19,9)				
	Jerrycan 20L	4	pcs	1200	(11,0)	4800	(44,0)				
User Interface	Urine diversion insert	1	pcs	2260	(20,7)	2260	(20,7)	500	(4,6)		
	Urinal	1	pcs	2500	(22,9)	2500	(22,9)				
	Wooden poles (0,15x0,15) 4m	4	pcs	1540	(14,1)	6160	(56,5)				
	Wooden poles (0,15x0,15) 2,5m	1	pcs	960	(8,8)	960	(8,8)				
	Wooden planks (0,15x0,025) 5m	17	pcs	825	(7,6)	14025	(128,7)	1500	(13,8)	15000	(137,6)
	Wooden slats (0,05x0,05) 5m	2	pcs	775	(7,1)	1550	(14,2)				
Superstructure	Wooden slats (0,05x0,05) 2,5m	2	pcs	390	(3,6)	780	(7,2)				
	Wooden slats (0,05x0,05) 3,5m	1	pcs	540	(5,0)	540	(5,0)				
	U-shaped post anchor	5	pcs	1450	(13,3)	7250	(66,5)				
	Corrugated zinc sheet (5,4x1)	2	pcs	4900	(45,0)	9800	(89,9)	500	(4,6)		
	Flyscreen aluminium mesh (2x0,9)	1	pcs	1100	(10,1)	1100	(10,1)				
	Hinge	2	pcs	340	(3,1)	680	(6,2)				
	Padbolt	1	pcs	260	(2,4)	260	(2,4)				
	Nails	1	kg	540	(5,0)	540	(5,0)				
Misc	Screws	1	kg	825	(7,6)	825	(7,6)	500	(4,6)		
	Metal handle	2	pcs	320	(2,9)	640	(5,9)				
	Paint	1	pcs	1250	(11,5)	1250	(11,5)				
	Silicone	1	pcs	785	(7,2)	785	(7,2)				
	Bucket for cover material	1	pcs	400	(3,7)	400	(3,7)				
Transport on island with truck								1000	(9,2)		
sum						82160	(753,8)	10750	(98,6)	15000	(137,6)
total sum								**107910**			(990,1)

prices in Vatu (year: 2015), exchange rate acc. World Bank: 108,99 Vt/US$

Table 10: BOQ (incl. material, transport and labour cost) of the Pour-Flush Toilet for Emae, Vanuatu.

	Item	Quantity	Unit	Cost/Unit Vatu	(US$)	Total Cost Vatu	(US$)	Cargo cost Vatu	(US$)	Labour cost Vatu	(US$)
	Cement (Dricon) á 40kg	3	bag	800	(7,3)	2400	(22,0)	1500	(13,8)		
Substructure	Sand	0,15	m^3								
	Coarse Aggregate	0,23	m^3								
	Steel mesh reinforcing 0,006x5,8x2,3	1	pcs	4675	(42,9)	4675	(42,9)	250	(2,3)		
User Interface	Toilet pedestal	1	pcs	5500	(50,5)	5500	(50,5)	500	(4,6)		
	Wooden poles (0,15x0,15) 3,5m	2	pcs	1350	(12,4)	2700	(24,8)				
	Wooden poles (0,15x0,15) 4,0m	2	pcs	1540	(14,1)	3080	(28,3)				
	Wooden planks (0,15x0,025) 5m	12	pcs	825	(7,6)	9900	(90,8)	1500	(13,8)		
	Wooden slats (0,05x0,05) 5m	1	pcs	775	(7,1)	775	(7,1)				
Superstructure	Wooden slats (0,05x0,05) 2,5m	1	pcs	390	(3,6)	390	(3,6)				
	Wooden slats (0,05x0,05) 3,5m	1	pcs	540	(5,0)	540	(5,0)			10000	(91,7)
	U-shaped post anchor	5	pcs	1450	(13,3)	7250	(66,5)				
	Corrugated zinc sheet (5,4x1)	1	pcs	4900	(45,0)	4900	(45,0)	500	(4,6)		
	Flyscreen aluminium mesh (2x0,9)	1	pcs	1100	(10,1)	1100	(10,1)				
	Hinge	2	pcs	340	(3,1)	680	(6,2)				
	Padbolt	1	pcs	260	(2,4)	260	(2,4)				
	Nails	1	kg	540	(5,0)	540	(5,0)				
Misc	Screws	1	kg	825	(7,6)	825	(7,6)	1000	(9,2)		
	DWV PVC pipe coupling	1	pcs	295	(2,7)	295	(2,7)				
	Paint	1	pcs	1250	(11,5)	1250	(11,5)				
	Silicone	1	pcs	785	(7,2)	785	(7,2)				
	Water barrel	1	pcs	2260	(20,7)	2260	(20,7)				
Transport on island with truck								1000	(9,2)		
sum						50105	(459,7)	6250	(57,3)	10000	(91,7)
total sum								**66355**			(608,8)

prices in Vatu (year: 2015), exchange rate acc. World Bank: 108,99 Vt/US$

in regard of the expected flood levels. Another possible design optimisation is to integrate the toilet into or adjacent to the residential building, provided there is enough space available. Thus, the costs for the superstructure can be reduced or avoided altogether. In case of the Pour-Flush latrine maybe costs can be saved by decreasing the lining of the pit head. At specific sites the local ground conditions might not demand for such an extensive lining.

PREFABRICATION AND MASS PRODUCTION can exploit the benefit of economies of scale. For example, mass production of prefabricated urine diversion user interfaces can be undertaken by local plastic or ceramic companies to lower costs. In case of the Pour-Flush Latrine, mass produced ring beams would be an alternative to decrease the costs of lining the pit. Additionally, prefabrication can be a measure to control and ensure the quality of the used materials (Ulrich et al., 2016). The calculation is done for single facilities, so all cost factors are determined for only one structure. However, when building several toilets simultaneously, significant cost savings can be realized. On the one hand, a quantity discount will be obtained, when buying lots of material at once. On the other hand, the transport costs will be reduced, when larger volumes of cargo are shipped. Further the labour costs can be reduced. According to the local carpenter Jakob Essau, it should be possible to build 3 to 4 UDDTs simultaneously within two to three days, resulting in a considerable reduction of labour costs (2015, personal comm., December 1). However, this can only be achieved if the prospective owners participate in the construction, supervised by the local carpenter. Encouraging household members to in-kind contributions of labour or materials reduces the financial costs for the household. Besides, participating in the construction process creates ownership of the facility, increasing the likelihood of careful use and operation. Further it enables the household to maintain and repair their facility themselves (Susana, 2009). *'Experience has shown that family members are willing to contribute their time and effort as substitute for local workmen who must be paid in cash'* (Susana, 2009, p. 5).

ALTERNATIVE BUILDING MATERIALS constitute the third and last pathway for achieving cost reductions. As shown in the BOQs above, the material costs constitute the major share of CapEx, presenting a high potential for cost savings. Yet substitution of materials for the UDDT substructure is not reasonable because a solid, waterproof construction of the dehydration vaults is inevitable. To guarantee save containment, proper treatment and longevity in view of upcoming flood events, the material quality of the substructure should not be compromised. Ulrich et al. (2016, p. 12) state, *'[i]n order for a system to function properly, its technical parameters have to meet the requirements of the socio-cultural and physical context (e.g. preference of sitting or squatting user interface, watertight construction for wet and flood-prone areas)'*. Nevertheless, substitution with local materials still has a large potential in regard of materials required for the superstructure.

During the field research on Emae, the chief of Finonge village (James Willie), his wife (Marie Willie) and a member of a local WASH committee (Christopher Daniel), introduced native plant species and their respective purpose for house constructions. The most important local plants that are traditionally used in construction are described in the Appendix (chapter 12). Local materials are usually free to harvest or comparatively cheap to commercial goods.

9.3 OPERATIONAL COSTS (OPEX)

In 2012, in the course of the WASHCost project, the IRC published minimum benchmarks for costing capital and recurrent expenditures of sanitation services in developing countries (see Table 11).

These figures are derived from the WASHCost database for capital, operation and maintenance expenditure, a second database for the implementation of sanitation programmes and a finally a study of capital maintenance expenditure. Distinguishing between three different sanitation systems, the benchmarks provide a range of expenditure for different cost factors (see Table 12). Information about recurrent costs for sanitation systems is scarce. The local context is highly significant when determining costs in developing countries. The level of service and value for

Table 11: Capital and recurrent expenditure benchmarks for sanitation services (IRC, 2012, p. 3, adapted).

Cost component	Latrine type in area of intervention	Cost ranges [min-max] in US$ 2011
Total capital expenditure (per latrine)	Traditional pit latrine with an impermeable slab (made often from local materials)	7-26
	Pit latrine with a concrete impermeable slab, or VIP type latrine with concrete superstructures (with ventilation pipe and screen to reduce odours and flies)	36-358
	Pour-flush or septic-tank latrine, often with a concrete or brick-lined pit/ tank with sealed impermeable slab, including a flushable pan	92-358
Total recurrent expenditure (per person, per year)	Traditional pit latrines with an impermeable slab (often made from local materials)	1.5-4.0
	VIP type latrines	2.5-8.5
	Pour-flush or septic-tank latrines	3.5-11.5

money is influenced by many social, institutional and political aspects. Nevertheless, if the expenditure is much lower than these benchmarks, then there is a high probability of the service being unsustainable (IRC, 2012).

When putting the figures into relation by converting these monetary values into percentage values, then the annual share of the OpEx for the traditional pit latrine is between 3.8% – 7,1% of the CapEx. For the pit latrine with concrete slab or VIP latrine the OpEx range from 1,1% – 2,8%. The OpEx of the Pour-Flush or septic tank latrines is around 1% of the CapEx.

Since both systems are planned for private households, it is intended that the routine operations (e.g. cleaning, changing jerrycans for urine storage or emptying the dehydration vaults) will be undertaken by the owners themselves. Rieck et al. (2012, p. 40) state, that *'[t]his is scenario is most practical in rural and peri-urban settings, where sufficient space for disposal and reuse of excreta is available',* which is the case on Emae. Here it must be mentioned that although no monetary value is assigned to operational tasks performed by the household members, there is indeed a value for the time spent to perform these tasks. However, assigning a financial value for the time spent for these activities is difficult, especially in countries where paid employment in rural areas is an exception, like it is the case in Vanuatu (Fonseca et al., 2011). Hence no monetary value for the time spent on operational tasks is included in the calculation.

As people are still cooking with wood fire and thus producing enough ash, there are no financial costs for the cover material required for the operation of the UDDT. The operational costs of the UDDT and the Pour-Flush latrine are estimated annually with 3% of the CapEx. This accounts primarily for minor repair works and cleaning materials required for daily operation. When converting the 3% share of CapEx into monetary values, it results in OpEx of 3237 Vt (29.70 US$) annually for the UDDT, and 1991 Vt (18.30 US$) for the Pour-Flush respectively (for a household size of five people). This is in line with the benchmark values form above.

9.4 Maintenance costs (CapManEx)

Beside OpEx, the IRC WASHCost benchmarks also determine figures for minimum CapManEx (see Table 12). Comparing the cost factor CapEx with CapManEx results in a share of 5.8% to 7.1% of the CapEx, that should be reinvested annually for maintenance purposes in case of traditional pit latrines. For the pit latrine with concrete slab or VIP latrine the CapManEx range is between 0.8% and 2,8%. In case of the Pour-Flush latrine or septic tank the annual share for CapManEx ranges from 1.7% to 2.2%.

Depending on the frequency and method of pit emptying, the subsequent treatment of the pit content in a (semi-) centralized treatment facility and finally the disposal of the treated faecal

Table 12: Breakdown of recurrent expenditure benchmarks for sanitation services (IRC, 2012, p. 3, adapted).

Breakdown of recurrent expenditure	**Cost ranges** [min-max] in US$ 2011 per person, per year		
	Traditional pit	VIP type latrines	Pour-flush or septic-tank latrines
Operational and minor maintenance expenditure	0.5-1	1-4	1-4
Capital maintenance expenditure	0.5-1.5	1-3	2-6
Expenditure on direct support	0.5-1.5	0.5-1.5	0.5-1.5
Total	**1.5-4**	**2.5-8.5**	**3.5-11.5**

sludge, a main share of the maintenance costs for sanitation systems accrues from these services (e.g. desludging with vacuum truck) (Burr & Fonseca, 2011; Tilley et al., 2014; Rieck et al., 2012). In the case of Emae no desludging, treatment and disposal infrastructure/service is available, so people abandon the pits when they are full and build new ones instead. Therefore, no costs incur for collection, conveyance and treatment services.

As stated above, CapManEx comprises the costs of restoring the same service level that was delivered when the system was new. Hence, re-siting a pit latrine once it is full is defined as CapManEx. An additional cost factor is included for re-siting the Pour-Flush facility (CapManEx re-siting). It consists of the material, transport and labour costs of the new substructure and moving the facility to the new site. According to the pit lifetime calculation, this has to be done every 5 years. Although no costs incur for desludging, treatment and disposal, a share of 6% of the CapEx is included annually to account for rehabilitation or replacement of broken parts.

On the one hand the UDDT consists of more parts that may have to be replaced due to deficiencies (e.g. urine piping, jerry cans). On the other hand, regularly re-siting the Pour-Flush superstructure is likely to increase required repair works. Hence the CapManEx of both systems are estimated equally with a share of 6% of the CapEx due every year, resulting in 6475 Vt (59.40 US$) per person per year for the UDDT, 3981 Vt (36.50 US$) for the Pour-Flush respectively.

9.5 Results of financial analysis

Based on the Bills of Quantity from above, the Present Value of future costs is calculated for both systems over a period of 20 years. The chosen discount rate is 10%. OpEx is determined annually with 3% and CapManEx with 6% of CapEx. The results of the present value analysis show that the Pour-Flush latrine is the preferred option compared to the UDDT (see Figure 27).

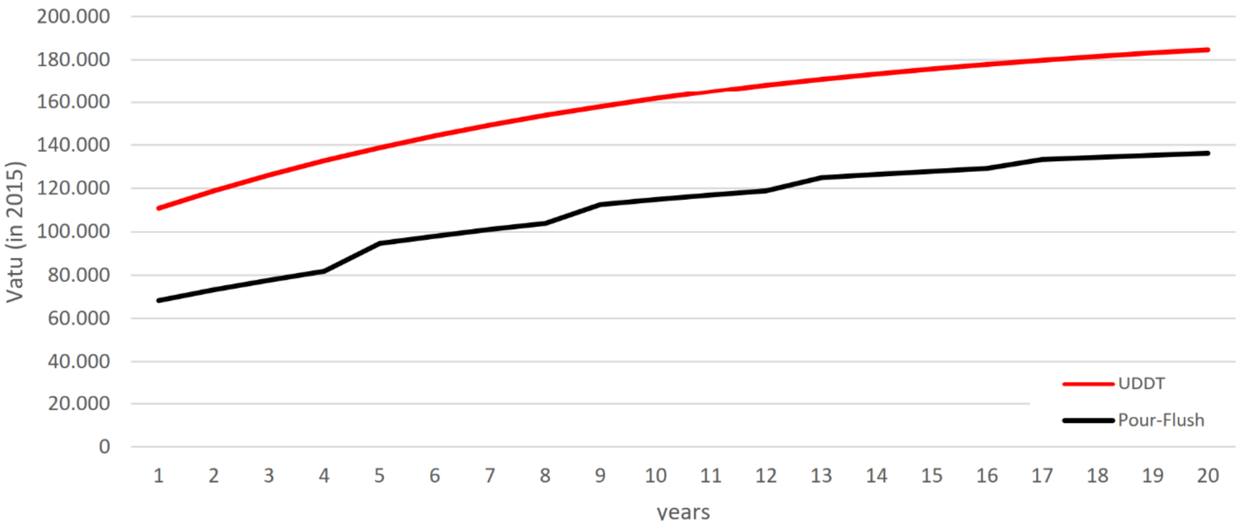

Figure 27: Cumulative Present Values (PV) of Urine-Diverting-Dry-Toilet and Pour-Flush Toilet in Vatu (year: 2015).

When all expenditures (CapEx, OpEx and CapManEx) are summed up over the whole lifespan of 20 years, the Pour-Flush Latrine induces Present Value costs of 136298 Vt (1250.60 US$) compared to the UDDT with 184707 Vt (1694.70 US$). The spreadsheets of the present value calculations are included in the Appendix (chapter 12, Figure 33 and Figure 34). A sensitivity analysis was conducted with various scenarios. However, the PV of future costs of the Pour-Flush Latrine stayed always lower than the PV of the UDDT.

PRESENT VALUE WITH SUBSTITUTED SUPERSTRUCTURE

Substituting the superstructure with local materials does not affect the ranking in between the two options, however Figure 28 depicts that the two cost curves converge. The Pour-Flush Latrine is still the preferred option after 20 years. The Present Value over the whole lifespan results in 80437 Vt (738.00 US$) for the Pour-Flush Latrine, and 109111 Vt (1001.10 US$) for the UDDT.

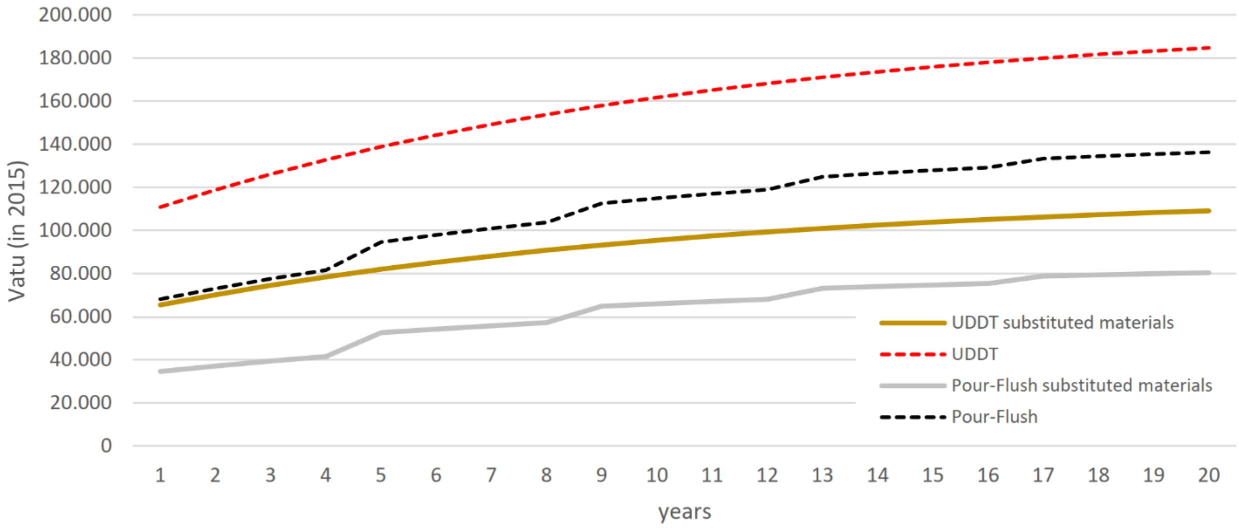

Figure 28: Cumulative Present Values (PV) with substituted materials for the superstructure of Urine-Diverting-Dry-Toilet (UDDT) and Pour-Flush (PF) Toilet in Vatu (year: 2015).

By encouraging the use of locally available materials and minimizing the amount of materials that have to be bought and transported, the most economical solution can be obtained. The costs for material and transport for the superstructure account for approximately 40.93% of the total CapEx for the UDDT, and 49.18% of the CapEx for the Pour-Flush Latrine respectively. Hence cutting these costs by substituting commercially procured materials with local ones significantly impacts the construction costs (see Figure 29).

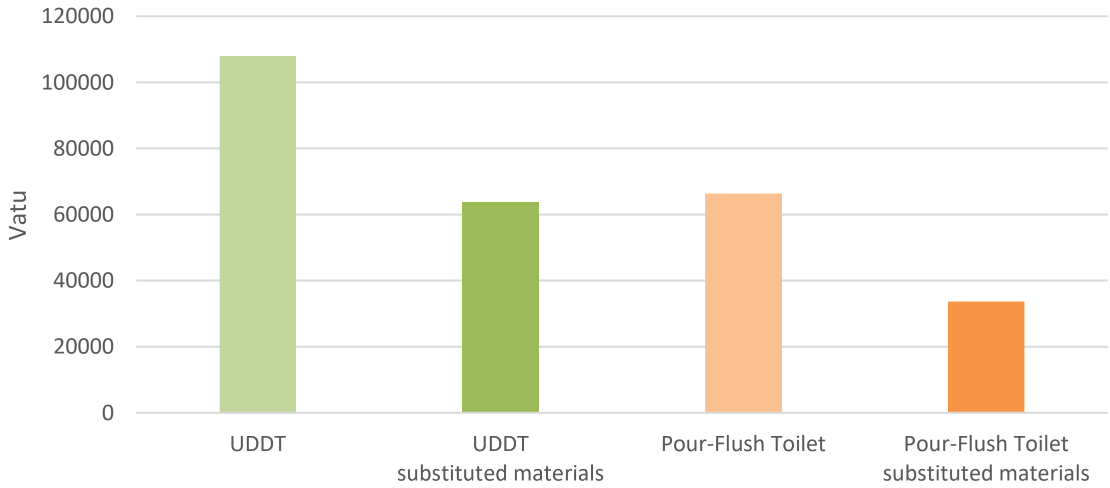

Figure 29: Construction costs of UDDT and Pour-Flush Latrine with commercial materials and local materials.

Beside this significant reduction of CapEx, also the CapManEx are reduced when people do not have to buy and import the materials needed for repairs. This fact is accounted in the calculation, as the CapManEx are determined as percentage value of the CapEx. This can be very beneficial as a report of UDDTs in Mozambique by Fodge et al. (2011, p. 6) states, *'[a]ccording to one local mason, one of the reasons why many UDDTs had deteriorated over time was that costs were too high for maintaining the UDDT. Apparently, good quality material to do the refurbishments is simply too expensive for the locals'.*

10. Conclusion and Discussion

Sanitation system analysis and selection

The sanitation system analysis (chapter 6) showed that the commonly used wet and dry Single Pit Latrines (i.e. ‘Bush Toilets’ and Pour-Flush Latrines) are not suitable for the conditions prevalent in many rural, coastal areas of Vanuatu. These coastal areas often feature high groundwater tables, are prone to floods and have a limited water supply. Especially Pour-Flush Latrines increase the risk of groundwater contamination, since flushwater facilitates the transport of pathogens from the thin unsaturated zone to the groundwater. Moreover, the hydraulic load in wet pits is higher than in dry pits, which further increases the risk. The common practice of digging pits to the water table, results in a direct contamination of groundwater resources. Pit Latrines can be raised above ground to overcome the problem by increasing the distance from the bottom of the pit to the saturated zone. Nevertheless, raising the pit results in a higher hydraulic gradient, increasing the risk of groundwater and surface water contamination that way. Another option is to seal the pits of Pit Latrines to prevent pollution of shallow groundwater resources. However, Sealed Pit Latrines require regular desludging services which are not available in Vanuatu except for the capital Port Vila. Pit latrines are at risk of being flooded during heavy rainfall or cyclone events causing coastal flooding. This results in pathogens being spread in the environment. Moreover, pit latrines can be inaccessible during and after floods or they are permanently unusable when collapsed or filled up with sediments. In general, the application of water-based sanitation systems like Pour-Flush Latrines should be avoided in areas suffering from water scarcity.

Composting toilets, featuring watertight vaults and cover doors, would be applicable regarding the underlying conditions. On-site research in Vanuatu showed that vault doors of inspected Composting Toilets were often poorly designed and far from being waterproof. Leachate seeping through the doors entails the risk of direct exposure of children, or indirect exposure via animals soiling the surrounding environment as well as groundwater pollution with faecal pathogens or increased nitrate levels. Moreover, treatment of faeces inside the vaults relies on thermophilic composting. In practice, the necessary temperatures cannot be attained with basic Composting Toilets on household level, as strong commitment and skilled management from the users or operators is required. Numerous studies showed that Composting Toilets often failed in producing a sufficiently sanitized material. Hence the implementation of this sanitation system is not recommended.

The Urine-Diverting-Dry-Toilet System seems to be the most suitable option for the prevalent conditions. Watertight vaults, built above ground, prevent the risk of contamination in areas with high water tables or prone to floods. Moreover, the waterless operation is reasonable in regard of upcoming extended drought periods due to climate change or during El Niño years. All other sanitation systems did not fulfil the determined criteria, or their implementation would be to complex or expensive for rural villages on small islands.

Design aspects of the UDDT

In order to make the UDDT system applicable for the conditions commonly found in rural, coastal areas of Vanuatu, the construction of a solid substructure is crucial. The foundation and the vaults including the vault doors have to be waterproof and robust to withstand flood events and prevent the contamination of surface- and groundwater bodies. Special attention must be paid to the design and construction of the vault doors. As stated above, these were one of the weak spots of the inspected toilets in Vanuatu. Semi-permanent vault doors that are sealed with mortar, can be a reliable option to achieve water tightness of the access holes. However, this can only be recommended, if a constant supply of sealing material (e.g. mortar) is available and if the users are able to re-install the doors. The second weak point of the inspected toilets in Vanuatu were improperly designed or poorly constructed ventilation pipes. Since the treatment of faecal matter is achieved through desiccation, functioning ventilation pipes are of high importance. T-caps at the end of pipes are needed to prevent rain from entering the vaults.

Beside these technical aspects, it is vital that users are involved in the design of their facilities. Community participation will enhance the user’s knowledge of the technology and increase ownership, which contributes to adequate use and maintenance. Further it is crucial to build capacities by instructing and training the people responsible for construction and maintenance. A local artisan may not perceive certain design aspects as important, especially if he just replicates a potentially inadequate design from an existing facility. Therefore, pivotal design elements may be overlooked or ignored if their purpose or function is not clearly apparent. The risk of poorly constructed facilities can be reduced by developing country specific design manuals (i.e. customised to the prevalent conditions, include technical drawings and illustrations of each construction step). If this information is not only accessible for the artisans but also for the owners, latter are able to monitor the quality of construction during daily inspections. If all stakeholders have common understanding of how the facility should be constructed, mistakes and deficiencies can be avoided in advance. After comprehensive training, members of local WASH committees can act as contact persons during construction and maintenance activities. Having someone with profound knowledge on-site would increase the quality of construction and prevent mistakes during implementation. Further, these key persons could be consulted if maintenance issues arise (e.g. procurement of replacement parts).

When a new sanitation system is introduced to a country or a community, the provision of a sound technical planning and the proper implementation of the system is important but covers only the ‘hardware’ part. The ‘software’ part including awareness raising, training in operation and maintenance, post-treatment, safe re-use practices for faeces and urine etc. are crucial for successful implementation.

FINANCIAL ANALYSIS

The financial analysis shows that the Present Value of the Pour-Flush Latrine is better in comparison to the UDDT. However, several aspects must be discussed in this regard: the service levels are different, benefits and external costs are not included, and the boundary of the analysis is set on household level.

First, a direct comparison can be misleading, without considering that each of the two systems delivers a different service level. Even if the Pour-Flush latrine will be operated and maintained correctly, it will be assessed as ‘limited’ or ‘no service’, since it causes significant environmental pollution through groundwater contamination or through spread of pit content during flood events. In contrast the UDDT will be assessed as ‘basic’ or ‘improved service’, since it fulfils all necessary requirements, provided it is built, operated and maintained correctly. Although the Pour-Flush latrine is the cheaper and probably desired option for many people, its application is not appropriate under the prevalent conditions.

This leads to another important consideration: the conducted financial analysis does not include broader economic costs nor benefits. Poor sanitation services have negative implications for the population, the environment and consequently for the economy. These external costs would include e.g. costs for water pollution, resulting health costs and costs for decreased productivity due to more sick days. Especially in regard of climate change and extended drought periods the lost opportunity to utilise groundwater resources as drinking water supply will be more crucial in the coming years. Looking back at the aftermath of TC Pam in 2015, communities relying entirely on rainwater harvesting were the most vulnerable, since many of the rainwater collection structures have been destroyed. The possibility to safely use groundwater resources, would foster the resilience of these communities by diversifying water supply to multiple sources. In terms of risk reduction this can be seen as the greatest benefit of an appropriate sanitation system in this context. Further the potential benefits of reusing human excreta are not included in the calculation. Urine fertilisation of crops in home gardens would lead to increased yields, making households more self-sufficient and generating higher income revenues when produce is sold at local markets. Since subsistence farming plays such an important role in rural areas, these benefits can be considerable. Moreover, there would be additional benefits of a well-functioning toilet on household level, which can hardly be monetized like improved privacy, dignity, convenience and status. Including all these potential benefits and external costs in a Net Present Value analysis would very likely make the UDDT the preferred option.

Since the boundary of the analysis was set at the household level, only direct financial costs accruing to the owner are included. However, a successful implementation on a project scale would induce auxiliary costs for management, regulation, surveillance, education and promotion. Especially costs of essential software components to achieve community acceptance, behaviour change, and long-term sustainability can be considerable for a new sanitation system. These costs would include issues like sanitation promotion, demand creation, awareness and educational campaigns and capacity development through trainings of stakeholders, which are all crucial elements to enable long-term success.

When compared to other countries, the estimated costs of the UDDT at the pilot site are considerable. This can be explained on the one hand by the geographical remoteness of Emae, and Vanuatu (i.e. island states) in general. Most construction materials are imported from overseas and further shipped to the island, which significantly raises the costs. On the other hand, the planned design presents a high-quality structure in order to be applicable and durable under the prevalent conditions. Due to the robust construction it can be assumed that the maintenance costs will be reduced compared to facilities of lower quality, especially after extreme events like floods or cyclones.

Since capital costs are a crucial component of the purchase decision of potential sanitation technologies (in particular for poor households), the costs of the system can be an obstacle. Subsidies might be required to reduce the financial burden for the households, which can further be utilised as an incentive to opt for this sustainable sanitation system. Economies of scale, prefabrication, design optimisation, alternative building materials, participation and in-kind contributions of owners can be opportunities to make the construction and maintenance more affordable.

The use of local materials reduces the costs considerably. Beside lower initial costs also the recurrent costs for maintenance will be decreased through usage of materials that are directly available on the island. This could enable households to do necessary repair work themselves, when using materials that they are familiar with. As a result, labour costs can be saved, and the ownership of the facility can be increased. Moreover, stored urine can be used to not only fertilise agricultural crops, but also plants used for construction (e.g. timber for walls and beams or palm leaves for thatched roofs). Consequently, households can decrease their dependence from imported materials, by growing and fertilising plants, to cover their own demand of building materials. Finally, traditional materials and construction techniques can increase the acceptance of this new, unfamiliar sanitation system.

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12. APPENDIX

LOCAL BUILDING MATERIALS FOR TIMBER CONSTRUCTIONS

The following is an excerpt showing some of the plants being traditionally used in construction on Emae. Since people have long-lasting experience and expertise in using these materials, it is safe to say that simple buildings, like a toilet superstructure, can easily be built with locally harvested and processed materials.

NATANGURA PALM (METROXYLON WARBURGII)

Metroxylon species are found on moist sites like in tropical lowland forests or freshwater swamps. They tolerate salinity, prolonged flooding and acidic soils. Since they grow on a wide variety of soils, including sand, they can be used as coastal protection against wave erosion. Under optimal conditions the growth rate is rapid, exceeding 1.50m per year (Elevitch, 2006).

In housing construction, Natangura palm leaves are commonly used to create thatched roofs (see Figure 30). The leaves, which can grow up to 3m, are cut from the tree when still green. Then they are heated over fire and separated from the inner stem of the leaves. Finally, they are folded in half and woven together to create a plane sheet. The durability of a roof thatched with Natangura leaves, depends on the inclination of the roof and the distance between each sheet. If the inclination is steep and the sheets are layered closely together (less than ~10cm), then it can last up to ten years. After TC Pam in 2015 most of the Natangura palms where destroyed on Emae (James Willie, 2015, personal comm., December 1).

Figure 30: Natangura palm leaves used for thatch roof on Emae, Vanuatu.

COCONUT PALM (COCOS NUCIFERA)

Coconut palms are the typical vegetation of sandy coastal areas throughout the tropics. They are also very common on inland sites, since people have been spreading them. Coconut palms can grow on a wide variety of soils (ranging from moderately acidic to alkaline), as long as waterlogging does not occur within the top meter (Elevitch, 2006). Coconut is of great importance for the local people and it is part of their everyday life. *'It is particularly important in the low islands of the Pacific where, in the absence of land-based natural resources, it provides almost all the necessities of life – food, drink, oil, medicine, fibre, timber, thatch, mats, fuel, and domestic utensils'* (Elevitch, 2006, p. 278).

For construction purposes coconut palms are commonly used as beams or planks. Since it grows abundantly on the island, the locals cut it themselves without any costs. Walls made from palm tree planks last for approximately 10 years (see Figure 31) (James Willie, 2015, personal comm., December 1).

Figure 31: Coconut palm planks used as wall covering for traditional house on Emae, Vanuatu.

Coconut palms are one of the most wind-tolerant plants in the world, with the ability to withstand cyclones if the roots are anchored deep enough. Due to the flexibility of the stem and fronds, the cross-sectional area exposed to the wind is decreased, thus reducing the drag forces the palm has to endure. Due to its dense and widespread roots coconut palms are important for coastal protection (Elevitch, 2006).

Whitewud (Endospermum Medullosum)

Whitewud trees can populate a wide variety of sites, preferably alluvial and freely drained soils, but also tolerates seasonally waterlogged or inundated soils. They can grow 20.00 – 40.00m tall at maturity. The first years are characterised by a very rapid growth of 2.50 – 3.00m annually. Environmentally they play an important role in revegetating various kinds of disturbed sites (e.g. storm damages), due to their pioneer characteristics. Further, trees of all ages have good cyclone resistance. In Vanuatu Whitewud is the major commercial timber species, it is in high demand locally as well as for export (Elevitch, 2006). On Emae whitewud timber is commonly used for construction of walls (see Figure 32) (James Willie, 2015, personal comm., December 1).

Figure 32: House made of Whitewud timber on Emae, Vanuatu.

Kasis (Leucaena leucocephala)

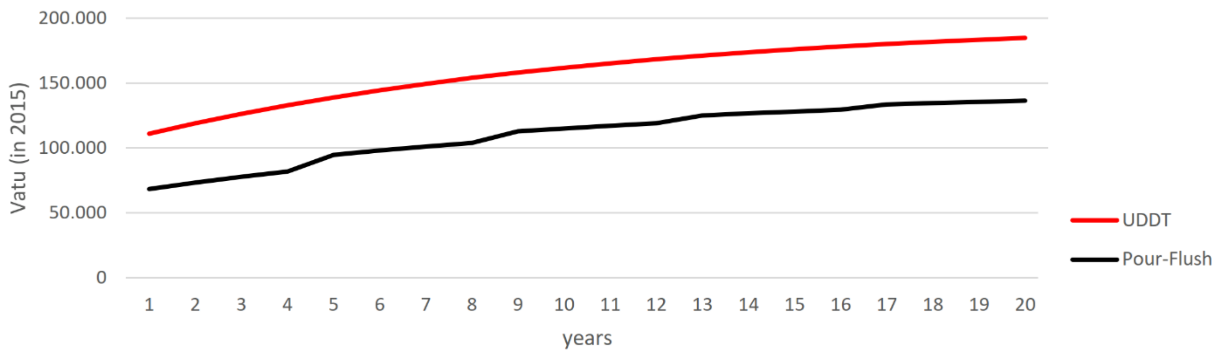
Kasis, also referred to as 'wild tamarind', is a small, shrubby and often highly branched tree with bole diameters between 10.00 – 35.00cm. It grows best on calcareous soils, is tolerant to salinity and alkaline conditions, but intolerant of acidic or waterlogged soils. Due to its small size it is used in construction when small timber dimensions are required (e.g. slats). The wood is hard and heavy, but easily workable for a wide range of carpentry purposes. (Orwa et al., 2009). Kasis trees with larger trunks are commonly used as main beams for bungalows (James Willie, 2015, personal comm., December 1). However, its durability is limited due to its susceptibility to termites and woodborers (Orwa et al., 2009).

BURAO (HIBISCUS TILIACEUS)

Burao also known as 'beach hibiscus' is a small tree, that typically grows 3.00 – 10.00m in height with a crooked, tangled, sprawling form. It is adapted to wide range of soils (acidic to alkaline) and it is often found in coastal or riverine areas. It can grow in waterlogged soils like shallow swamps (Elevitch, 2006). In housing construction its wood is valued for its lightness and flexibility and therefore often used as beams or slats (James Willie, 2015, personal comm., December 1).

Year	Discount factor	CapEx Vatu	CapEx (US$)	OpEx Vatu	OpEx (US$)	discounted OpEx Vatu	discounted OpEx (US$)	CapManEx Vatu	CapManEx (US$)	discounted CapManEx Vatu	discounted CapManEx (US$)	Cumulative PV Vatu	Cumulative PV (US$)
1	0,909	107.910	(990,1)	3.237	(29,7)	2.943	(27,0)	0	(0,0)	0	(0,0)	110.853	(1.017,1)
2	0,826			3.237	(29,7)	2.675	(24,5)	6.475	(59,4)	5.351	(49,1)	118.879	(1.090,7)
3	0,751			3.237	(29,7)	2.432	(22,3)	6.475	(59,4)	4.864	(44,6)	126.176	(1.157,7)
4	0,683			3.237	(29,7)	2.211	(20,3)	6.475	(59,4)	4.422	(40,6)	132.809	(1.218,5)
5	0,621			3.237	(29,7)	2.010	(18,4)	6.475	(59,4)	4.020	(36,9)	138.840	(1.273,9)
6	0,564			3.237	(29,7)	1.827	(16,8)	6.475	(59,4)	3.655	(33,5)	144.322	(1.324,2)
7	0,513			3.237	(29,7)	1.661	(15,2)	6.475	(59,4)	3.322	(30,5)	149.306	(1.369,9)
8	0,467			3.237	(29,7)	1.510	(13,9)	6.475	(59,4)	3.020	(27,7)	153.836	(1.411,5)
9	0,424			3.237	(29,7)	1.373	(12,6)	6.475	(59,4)	2.746	(25,2)	157.955	(1.449,3)
10	0,386			3.237	(29,7)	1.248	(11,5)	6.475	(59,4)	2.496	(22,9)	161.699	(1.483,6)
11	0,350			3.237	(29,7)	1.135	(10,4)	6.475	(59,4)	2.269	(20,8)	165.103	(1.514,8)
12	0,319			3.237	(29,7)	1.032	(9,5)	6.475	(59,4)	2.063	(18,9)	168.198	(1.543,2)
13	0,290			3.237	(29,7)	938	(8,6)	6.475	(59,4)	1.875	(17,2)	171.011	(1.569,1)
14	0,263			3.237	(29,7)	852	(7,8)	6.475	(59,4)	1.705	(15,6)	173.569	(1.592,5)
15	0,239			3.237	(29,7)	775	(7,1)	6.475	(59,4)	1.550	(14,2)	175.893	(1.613,8)
16	0,218			3.237	(29,7)	705	(6,5)	6.475	(59,4)	1.409	(12,9)	178.007	(1.633,2)
17	0,198			3.237	(29,7)	640	(5,9)	6.475	(59,4)	1.281	(11,8)	179.929	(1.650,9)
18	0,180			3.237	(29,7)	582	(5,3)	6.475	(59,4)	1.165	(10,7)	181.675	(1.666,9)
19	0,164			3.237	(29,7)	529	(4,9)	6.475	(59,4)	1.059	(9,7)	183.263	(1.681,5)
20	0,149			3.237	(29,7)	481	(4,4)	6.475	(59,4)	962	(8,8)	**184.707**	**(1.694,7)**
Sum		107.910	(990,1)	64.746	(594,1)	27.561	(252,9)	123.017	(1.128,7)	49.236	(451,7)		

costs in Vatu (year: 2015); exchange rate acc. World Bank: 108,99 Vt/US$ (year: 2015)



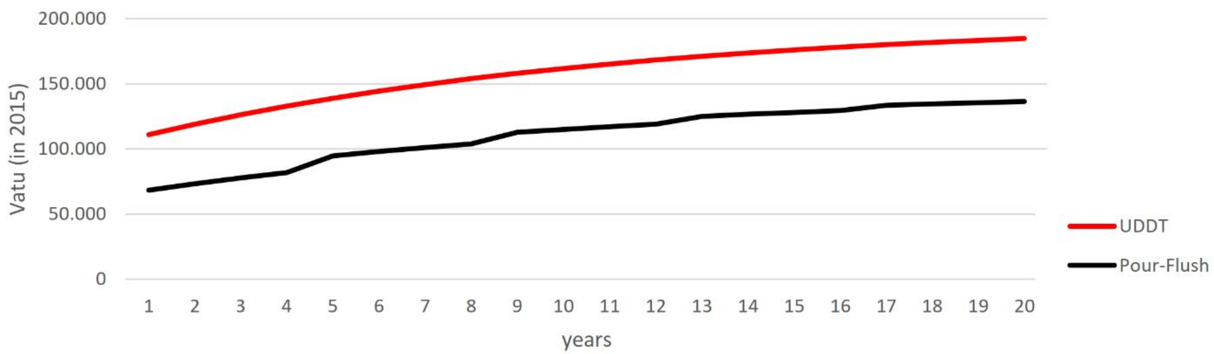
Lifetime	20 years	
Discount rate	10 %	
CapManEx	6 % of CapEx	
OpEx	3 % of CapEx	

	Vatu	(US$)
CapEx	107.910	(990,1)
disc. OpEx	27.561	(252,9)
disc. CapManEx	49.236	(451,7)
PV	**184.707**	**(1.694,7)**

Figure 33: Present Value calculation of Urine-Diverting-Dry-Toilets for Emae, Vanuatu.

Year	Discount factor	CapEx		OpEx		discounted OpEx		CapManEx		discounted CapManEx		CapManEx re-siting		disc. CapManEx re-siting		Cumulative PV	
		Vatu	(US$)	Vatu	(US$)	Vatu	(US$)	Vatu	(US$)	Vatu	(US$)	Vatu	(US$)	Vatu	(US$)	Vatu	(US$)
1	0,909	66.355	(608,8)	1.991	(18,3)	1.810	(16,6)	0	(0,0)	0	(0,0)	0	(0,0)	0	(0,0)	68.165	(625,4)
2	0,826			1.991	(18,3)	1.645	(15,1)	3.981	(36,5)	3.290	(30,2)	0	(0,0)	0	(0,0)	73.100	(670,7)
3	0,751			1.991	(18,3)	1.496	(13,7)	3.981	(36,5)	2.991	(27,4)	0	(0,0)	0	(0,0)	77.587	(711,9)
4	0,683			1.991	(18,3)	1.360	(12,5)	3.981	(36,5)	2.719	(24,9)	0	(0,0)	0	(0,0)	81.666	(749,3)
5	0,621			1.991	(18,3)	1.236	(11,3)	3.981	(36,5)	2.472	(22,7)	14.825	(136,0)	9.205	(84,5)	94.579	(867,8)
6	0,564			1.991	(18,3)	1.124	(10,3)	3.981	(36,5)	2.247	(20,6)	0	(0,0)	0	(0,0)	97.950	(898,7)
7	0,513			1.991	(18,3)	1.022	(9,4)	3.981	(36,5)	2.043	(18,7)	0	(0,0)	0	(0,0)	101.015	(926,8)
8	0,467			1.991	(18,3)	929	(8,5)	3.981	(36,5)	1.857	(17,0)	0	(0,0)	0	(0,0)	103.801	(952,4)
9	0,424			1.991	(18,3)	844	(7,7)	3.981	(36,5)	1.688	(15,5)	14.825	(136,0)	6.287	(57,7)	112.621	(1.033,3)
10	0,386			1.991	(18,3)	767	(7,0)	3.981	(36,5)	1.535	(14,1)	0	(0,0)	0	(0,0)	114.923	(1.054,4)
11	0,350			1.991	(18,3)	698	(6,4)	3.981	(36,5)	1.395	(12,8)	0	(0,0)	0	(0,0)	117.016	(1.073,6)
12	0,319			1.991	(18,3)	634	(5,8)	3.981	(36,5)	1.269	(11,6)	0	(0,0)	0	(0,0)	118.919	(1.091,1)
13	0,290			1.991	(18,3)	577	(5,3)	3.981	(36,5)	1.153	(10,6)	14.825	(136,0)	4.294	(39,4)	124.943	(1.146,4)
14	0,263			1.991	(18,3)	524	(4,8)	3.981	(36,5)	1.048	(9,6)	0	(0,0)	0	(0,0)	126.516	(1.160,8)
15	0,239			1.991	(18,3)	477	(4,4)	3.981	(36,5)	953	(8,7)	0	(0,0)	0	(0,0)	127.945	(1.173,9)
16	0,218			1.991	(18,3)	433	(4,0)	3.981	(36,5)	866	(7,9)	0	(0,0)	0	(0,0)	129.245	(1.185,8)
17	0,198			1.991	(18,3)	394	(3,6)	3.981	(36,5)	788	(7,2)	14.825	(136,0)	2.933	(26,9)	133.360	(1.223,6)
18	0,180			1.991	(18,3)	358	(3,3)	3.981	(36,5)	716	(6,6)	0	(0,0)	0	(0,0)	134.434	(1.233,5)
19	0,164			1.991	(18,3)	325	(3,0)	3.981	(36,5)	651	(6,0)	0	(0,0)	0	(0,0)	135.410	(1.242,4)
20	0,149			1.991	(18,3)	296	(2,7)	3.981	(36,5)	592	(5,4)	0	(0,0)	0	(0,0)	**136.298**	**(1.250,6)**
Sum		66.355	(608,8)	39.813	(365,3)	16.948	(155,5)	75.645	(694,1)	30.276	(277,8)	59.300	(544,1)	22.720	(208,5)		

costs in Vatu (year: 2015); exchange rate acc. World Bank: 108,99 Vt/US$ (year: 2015)



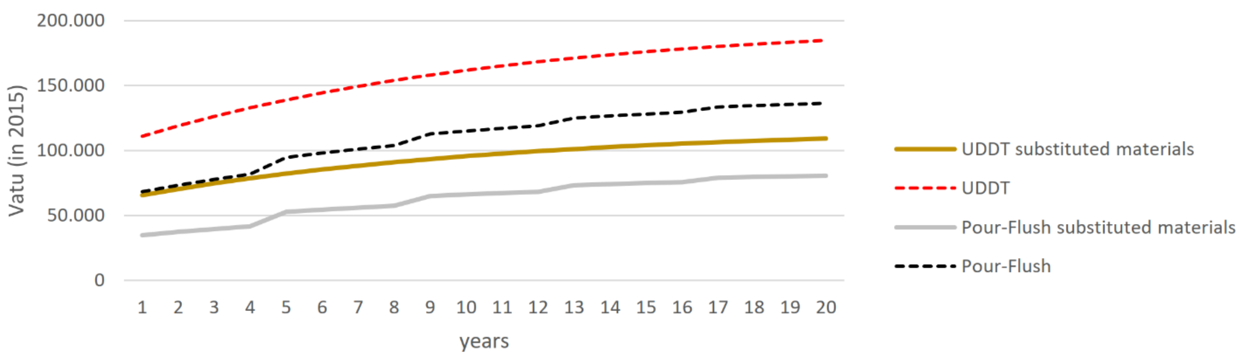
Lifetime	20	years
Pit lifetime	5	years
Re-siting costs	14825	Vatu
Discount rate	10	%
CapManEx	6	% of CapEx
OpEx	3	% of CapEx

	Vatu	(US$)
CapEx	66.355	(608,8)
disc. OpEx	16.948	(155,5)
disc. CapManEx	52.995	(486,2)
PV	**136.298**	**(1.250,6)**

Figure 34: Present Value calculation of Pour-Flush Toilets for Emae, Vanuatu.

Year	Discount factor	CapEx Vatu	CapEx (US$)	OpEx Vatu	OpEx (US$)	discounted OpEx Vatu	discounted OpEx (US$)	CapManEx Vatu	CapManEx (US$)	discounted CapManEx Vatu	discounted CapManEx (US$)	Cumulative PV Vatu	Cumulative PV (US$)
1	0,909	63.745	(584,9)	1.912	(17,5)	1.739	(16,0)	0	(0,0)	0	(0,0)	65.484	(600,8)
2	0,826			1.912	(17,5)	1.580	(14,5)	3.825	(35,1)	3.161	(29,0)	70.225	(644,3)
3	0,751			1.912	(17,5)	1.437	(13,2)	3.825	(35,1)	2.874	(26,4)	74.535	(683,9)
4	0,683			1.912	(17,5)	1.306	(12,0)	3.825	(35,1)	2.612	(24,0)	78.454	(719,8)
5	0,621			1.912	(17,5)	1.187	(10,9)	3.825	(35,1)	2.375	(21,8)	82.016	(752,5)
6	0,564			1.912	(17,5)	1.079	(9,9)	3.825	(35,1)	2.159	(19,8)	85.254	(782,2)
7	0,513			1.912	(17,5)	981	(9,0)	3.825	(35,1)	1.963	(18,0)	88.198	(809,2)
8	0,467			1.912	(17,5)	892	(8,2)	3.825	(35,1)	1.784	(16,4)	90.875	(833,8)
9	0,424			1.912	(17,5)	811	(7,4)	3.825	(35,1)	1.622	(14,9)	93.308	(856,1)
10	0,386			1.912	(17,5)	737	(6,8)	3.825	(35,1)	1.475	(13,5)	95.520	(876,4)
11	0,350			1.912	(17,5)	670	(6,1)	3.825	(35,1)	1.341	(12,3)	97.530	(894,9)
12	0,319			1.912	(17,5)	609	(5,6)	3.825	(35,1)	1.219	(11,2)	99.358	(911,6)
13	0,290			1.912	(17,5)	554	(5,1)	3.825	(35,1)	1.108	(10,2)	101.020	(926,9)
14	0,263			1.912	(17,5)	504	(4,6)	3.825	(35,1)	1.007	(9,2)	102.531	(940,7)
15	0,239			1.912	(17,5)	458	(4,2)	3.825	(35,1)	916	(8,4)	103.904	(953,3)
16	0,218			1.912	(17,5)	416	(3,8)	3.825	(35,1)	832	(7,6)	105.153	(964,8)
17	0,198			1.912	(17,5)	378	(3,5)	3.825	(35,1)	757	(6,9)	106.288	(975,2)
18	0,180			1.912	(17,5)	344	(3,2)	3.825	(35,1)	688	(6,3)	107.320	(984,7)
19	0,164			1.912	(17,5)	313	(2,9)	3.825	(35,1)	625	(5,7)	108.258	(993,3)
20	0,149			1.912	(17,5)	284	(2,6)	3.825	(35,1)	569	(5,2)	**109.111**	**(1.001,1)**
Sum		63.745	(584,9)	38.247	(350,9)	16.281	(149,4)	72.669	(666,8)	29.085	(266,9)		

costs in Vatu (year: 2015); exchange rate acc. World Bank: 108,99 Vt/US$ (year: 2015)



Lifetime	20 years
Discount rate	10 %
CapManEx	6 % of CapEx
OpEx	3 % of CapEx

	Vatu	(US$)
CapEx	63.745	(584,9)
disc. OpEx	16.281	(149,4)
disc. CapManEx	29.085	(266,9)
PV	**109.111**	**(1.001,1)**

Figure 35: Present Value calculation of Urine-Diverting-Dry-Toilets with substituted materials for Emae, Vanuatu.

Year	Discount factor	CapEx Vatu	CapEx (US$)	OpEx Vatu	OpEx (US$)	discounted OpEx Vatu	discounted OpEx (US$)	CapManEx Vatu	CapManEx (US$)	discounted CapManEx Vatu	discounted CapManEx (US$)	CapManEx re-siting Vatu	CapManEx re-siting (US$)	disc. CapManEx re-siting Vatu	disc. CapManEx re-siting (US$)	Cumulative PV Vatu	Cumulative PV (US$)
1	0,909	33.720	(309,4)	1.012	(9,3)	920	(8,4)	0	(0,0)	0	(0,0)	0	(0,0)	0	(0,0)	34.640	(317,8)
2	0,826			1.012	(9,3)	836	(7,7)	2.023	(18,6)	1.672	(15,3)	0	(0,0)	0	(0,0)	37.148	(340,8)
3	0,751			1.012	(9,3)	760	(7,0)	2.023	(18,6)	1.520	(13,9)	0	(0,0)	0	(0,0)	39.428	(361,8)
4	0,683			1.012	(9,3)	691	(6,3)	2.023	(18,6)	1.382	(12,7)	0	(0,0)	0	(0,0)	41.501	(380,8)
5	0,621			1.012	(9,3)	628	(5,8)	2.023	(18,6)	1.256	(11,5)	14.825	(136,0)	9.205	(84,5)	52.590	(482,5)
6	0,564			1.012	(9,3)	571	(5,2)	2.023	(18,6)	1.142	(10,5)	0	(0,0)	0	(0,0)	54.303	(498,2)
7	0,513			1.012	(9,3)	519	(4,8)	2.023	(18,6)	1.038	(9,5)	0	(0,0)	0	(0,0)	55.861	(512,5)
8	0,467			1.012	(9,3)	472	(4,3)	2.023	(18,6)	944	(8,7)	0	(0,0)	0	(0,0)	57.276	(525,5)
9	0,424			1.012	(9,3)	429	(3,9)	2.023	(18,6)	858	(7,9)	14.825	(136,0)	6.287	(57,7)	64.851	(595,0)
10	0,386			1.012	(9,3)	390	(3,6)	2.023	(18,6)	780	(7,2)	0	(0,0)	0	(0,0)	66.021	(605,7)
11	0,350			1.012	(9,3)	355	(3,3)	2.023	(18,6)	709	(6,5)	0	(0,0)	0	(0,0)	67.084	(615,5)
12	0,319			1.012	(9,3)	322	(3,0)	2.023	(18,6)	645	(5,9)	0	(0,0)	0	(0,0)	68.051	(624,4)
13	0,290			1.012	(9,3)	293	(2,7)	2.023	(18,6)	586	(5,4)	14.825	(136,0)	4.294	(39,4)	73.225	(671,8)
14	0,263			1.012	(9,3)	266	(2,4)	2.023	(18,6)	533	(4,9)	0	(0,0)	0	(0,0)	74.024	(679,2)
15	0,239			1.012	(9,3)	242	(2,2)	2.023	(18,6)	484	(4,4)	0	(0,0)	0	(0,0)	74.750	(685,8)
16	0,218			1.012	(9,3)	220	(2,0)	2.023	(18,6)	440	(4,0)	0	(0,0)	0	(0,0)	75.411	(691,9)
17	0,198			1.012	(9,3)	200	(1,8)	2.023	(18,6)	400	(3,7)	14.825	(136,0)	2.933	(26,9)	78.944	(724,3)
18	0,180			1.012	(9,3)	182	(1,7)	2.023	(18,6)	364	(3,3)	0	(0,0)	0	(0,0)	79.490	(729,3)
19	0,164			1.012	(9,3)	165	(1,5)	2.023	(18,6)	331	(3,0)	0	(0,0)	0	(0,0)	79.986	(733,9)
20	0,149			1.012	(9,3)	150	(1,4)	2.023	(18,6)	301	(2,8)	0	(0,0)	0	(0,0)	**80.437**	**(738,0)**
Sum		33.720	(309,4)	20.232	(185,6)	8.612	(79,0)	38.441	(352,7)	15.385	(141,2)	59.300	(544,1)	22.720	(208,5)		

costs in Vatu (year: 2015); exchange rate acc. World Bank: 108,99 Vt/US$ (year: 2015)

Lifetime	20	years
Pit lifetime	5	years
Re-siting costs	14.825	Vatu
Discount rate	10	%
CapManEx	6	% of CapEx
OpEx	3	% of CapEx

	Vatu	(US$)
CapEx	33.720	(309,4)
disc. OpEx	8.612	(79,0)
disc. CapManEx	38.105	(349,6)
PV	**80.437**	**(738,0)**

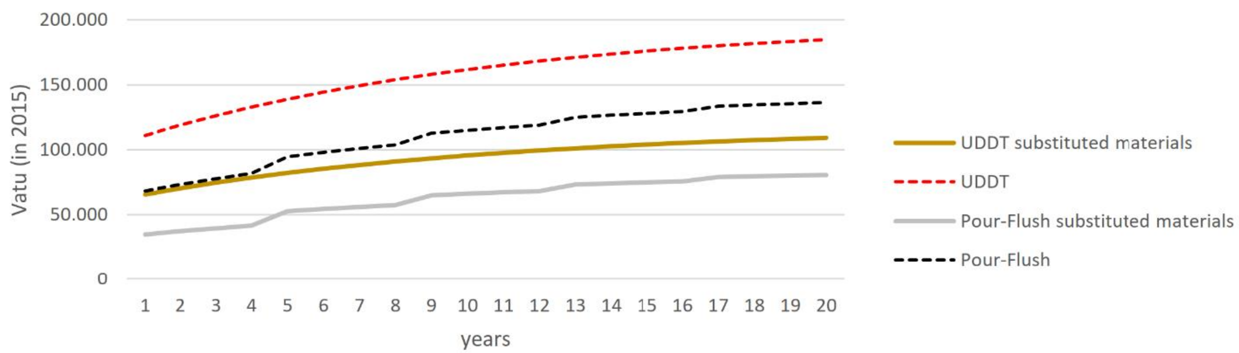


Figure 36: Present Value calculation of Pour-Flush Toilets with substituted materials for Emae, Vanuatu.

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14. Affirmation

I certify, that the master thesis was written by me, not using sources and tools other than quoted and without use of any other illegitimate support.

Furthermore, I confirm that I have not submitted this master thesis either nationally or internationally in any form.

Vienna, 22.10.2019 Hans Christian Dworak